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More specifically, we describe the prototype of lock-in, bipolar preamplifier and flux counter implemeted by our team.
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FINAL TECHNICAL REPORT:

SDIO-SBIR Phase-I Project

COMPUTER-ORIENTED, MULTICHANNEL, DIRECT-CURRENT,
SUPERCONDUCTING QUANTUM INTERFERENCE DEVICE

~~Towards Computer Oriented Multichannel DC-SQUID System~~

Abstract:

We describe the ARC effort leading towards the computer oriented multichannel DC-SQUID system.

More specifically, we describe the prototype of lock-in, bipolar preamplifier and flux counter implemented by our team.

The results of tests are quoted and show that our DC-SQUID electronics compare favorably with both commercially available BTI-Dynabias and Berkeley readout electronics. More specifically, our system seems to be more user friendly and easier to interface to the computer.

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1.0 IDENTIFICATION AND SIGNIFICANCE OF THE PROBLEM

1.1 Introduction

Applied Research Corporation (ARC) proposed the development of a portable, multichannel Superconducting Quantum Interference Device (SQUID) system operating at liquid nitrogen temperature.

This development was a collaborative effort of scientists from ARC and the group of Dr. M. Cromar, NBS, Boulder.

In the Phase-I effort we:

- tested the DC-SQUID's produced by NBS-Boulder, and some other producers;
- reviewed the possibility of high T_c implementation of DC-SQUID's (including radiation modification technique);
- designed/tested inexpensive multichannel electronics for SQUID signal conditioning and digitization.

In the following section, we describe the project motivation. In Section 2 our effort is briefly described. The development/test of the first prototype of DC-SQUID electronics is described in Section 3. In Section 4, we describe the second prototype. Finally, many of the technical details can be found in Appendices.

1.2 Scientific and Technological Interest of SQUID's

Superconducting Quantum Interference Devices (SQUID's) are ultrasensitive electronic devices. Their unprecedented sensitivity to a change of magnetic field, $\Delta\phi = 5\times10^{-5}\phi_0/\sqrt{Hz}$ wherein $\phi_0 = 2.\times10^{-7}$ Gcm^2, permits measurements with precision approaching the quantum limit. DC-SQUID's with a noise of a few n have been developed and used both to directly measure magnetic fields and as very low noise amplifiers. They are often used as "zero sensors" in bridge configurations and are increasingly used in all types of electronic applications, e.g., in current and voltage measurements. Typically, SQUID's are rather slow, integrating devices but DC-SQUID's have been developed with bandwidths of a few hundred MHz.

Of special interest is the use of cryoelectronics, e.g. DC-SQUID's in readout of focal plane photon detectors spanning a wide range of electromagnetic radiation, especially of IR/visible detectors with excellent spatial resolution. Two types of such devices: the superconducting granular detector (SGD) and solid-state photomuliplier with event localization via magnetic sensing will be described in the Phase-II proposal. These detectors are especially important in SDIO applications because of:

- excellent spatial resolution (10^4x10^4 pixels seems to be possible)
- radiation hardness up to 100 MRad.

These detectors include novel monolithic focal plane arrays and the optimal readout uses superconducting electronics, e.g., Josephson junctions and SQUID's. More generally, in all sensor applications using the low temperature sensors the use of arrays of ultrasensitive superconducting preamplifiers is of considerable advantage.

1.3 Limitations of Existing SQUID Technology and Importance of Proposed Improvements

The main disadvantage of SQUID's is the need for very low temperatures; they are usually operated in liquid helium. Thus, with some exceptions, SQUID applications are limited to laboratory measurements. SQUID's are furthermore very sensitive devices, requiring highly qualified specialists as operators, and the required cryogenics are usually bulky. Another disadvantage of SQUID's is their price, typically $15,000-$20,000 per channel. This limits their application to "single channel" measurements and excludes many interesting "sensor" applications wherein SQUID's operate as a "zero sensor" or preamplifier in an <u>array</u> of sensors (transducers or detectors).

The development of high T_C superconductivity may lead to considerable changes in SQUID technology. First, operation in liquid nitrogen permits the use of simple, small and rugged cryostats; <u>portble</u> systems seem to be possible, as for example with liquid nitrogen cooled Ge(Li) semiconductor detectors which are often used as self-contained, transportable units. Second, the <u>diminished price of cryogenics motivates development of low cost, miniaturized room temperature electronics necessary for SQUID signal conditioning and measurements</u>. The development of such electronics is simplified, because due to Johnson noise limiting performance of high temperature SQUID's the somewhat high noise of the readout electronics is acceptable. We believe that the price of the readout electronics can be decreased by about a factor of 10, and a multichannel SQUID system with a price of $2,000-$3,000 per channel seems possible.

Thus, we expect that the applications of SQUID's will be extended from cryogenic laboratories to a plurality of diversified applications. Today, SQUID's are top-of-the-line, ultrasensitive devices; tomorrow, multichannel, system-oriented applications will become more and more important. For many years, the trend was to develop increasingly sensitive SQUID's without taking into consideration the economics of their use. In the future, devices with excellent performance (though somewhat inferior to liquid helium SQUID's) will be miniaturized and their price considerably reduced. Another aspect of SQUID development is the need for standardization. Until recently, all set-ups using SQUID's were built around the SQUID. In the future, SQUID's will become just one of the elements of a complex, computer-oriented measuring system. Thus, when developing multichannel SQUID electronics we decided upon the NIM and IEEE-488 standards.

Several types of SQUID's have used "gradiometric" pickup loops with good rejection of "common-mode" magnetic noise, e.g. the "two-hole" SQUID or "fractional-turn" SQUID[1]. More recently, plane geometry gradiometers using a superconducting flux transformer have been used[2]. More specifically, the group of Dr. M. Cromar, NBS-Boulder has developed[3] and tested a Double Transformer (DT)-coupled DC SQUID with low noise, an input inductance of 1.7 μH, and smooth input-output characteristics. The minimum detectable energy (MDE) per unit bandwidth referred to the SQUID loop is 10h, and further improvement to MDE ≈ 5h seems possible. In collaboration with ARC, the NBS group is developing a DT-coupled DC-SQUID which will feature an input inductance of 10 μH; this will considerably facilitate the use of DC-SQUID's in the readout of superconducting particle/radiation detectors.

The progress in SQUID instrumentation for measurements of magnetic fields depends on

- improvement of the <u>intrinsic</u> resolution of SQUID's;
- better coupling of SQUID's to the external world.

The progress in reducing the intrinsic noise of SQUID's has been very rapid, especially following the development of DC-SQUID's. An intrinsic energy sensitivity of a few h was achieved[4], and sources of noise in tunnel junction DC-SQUID's were analyzed by the J. Clarke group[5], for example. This progress is, however, dependent on the process in modern lithography necessary to build very low capacitance tunnel junctions. The materials of preference have been refractory metals and Pb/In alloys. We believe, however, that <u>reproducible</u> submicron lithography resolution with high T_c superconductors will be a difficult task, and that SQUID's operating in liquid nitrogen (LN_2) will have a typical noise of about $\Delta\phi \approx 10^{-4}\phi_o/\sqrt{Hz}$. Thus, because of a higher Johnson noise and the difficulty of producing very small junctions, LN_2 SQUID's will be about a factor of ten less sensitive than the best LHe DC-SQUID's. We should like to point out that such LN_2 SQUID's have already been produced, using a variety of techniques (R. Koch, IBM - private information)..

1.4 Towards High T_c DC-SQUID's

The recent discovery of ceramic superconductors with high T_c opens the way for the development of superconducting devices operating at LN_2 temperature (77°K). Of particular interest is the possibility of building liquid nitrogen SQUID's.

The first SQUID to be operated in LN_2 were RF-SQUID's, e.g. an RF-SQUID developed by the NBS-Boulder group. This SQUID was formed from a ring of Y-Ba-Cu-O broken in a cryogenic environment and then recontacted. Thus, this is a typical point-contact device and the noise performance at 4.2°K is comparable to other such devices, $3x10^{-4}\phi_o/\sqrt{Hz}$. High temperature operation, however, imposes a limitation due to thermal fluctuations/~0.5kT per degree of freedom and generates a mean-square fluctuation in a SQUID of $1/2\ \phi_N^2/L$, where L is the SQUID inductance; thus at 77°K, L should be $L << 10^{-9}H$. In LN_2, the SQUID sensitivity was about $2x10^{-2}\phi_o/\sqrt{Hz}$. More recently, it was improved to about $5x10^{-3}\phi_o/\sqrt{Hz}$ (M. Cromar, private communication). In conclusion, the NBS-group (as well as others) has demonstrated the operation of an RF-SQUID magnetometer and measured reasonable sensitivity. Although useful for laboratory measurements, the instability of the break (or crack junction) considerably limits the practical applications of such a device.

It is obvious that future LN_2-operated SQUID's will be produced using thin film techniques. Koch et al. have successfully operated at 68°K a one layer, thin film DC SQUID with long, granular, weak-link bridge. Taking into consideration the crucial importance of the oxidation level in Y-Ba-Cu-O systems, it seems probable that a kind of Dayem bridge will be used, rather than tunnel junctions. Actually, thallium/bismuth films seems to be better than 1-2-3 compounds.

Since the discovery of superconductivity at high temperatures in the rare and alkaline earth's copper perovskites, the deposition of thin superconducting films of these materials has been demonstrated by a number of groups. Films which are typically 1 micrometer thick have been deposited by vacuum evaporation of the metals in the presence of oxygen, magnetron and ion beam sputtering in argon from a composite or dual targets and by laser evaporation from a superconducting target. Thicker films of 10-250 µm thickness have been deposited by plasma spraying of the powder of the superconducting material

followed by annealing. All deposited films, however, had to be annealed under proper conditions to produce the superconducting phase.

After producing the film, the next step is patterning. Usually, one uses photolithography, but the chemical sensitivity of Y-Ba-Cu-O films make the use of chemical etching difficult. Essentially two structures should be built

- a planar geometry pickup loop with superconducting transformer(s);
- a DC SQUID with two weak links.

The first task requires patterning of thick films with 10-20 µm width and micron precision. The second task, creating weak junctions, requires producing submicron structures and is technologically the most demanding step of DC-SQUID fabrication.

For potential applications in electronic devices and for many electrical measurements, it is important to pattern the films. The IBM group (M. Schuermann et al., "Magnetron Sputtering and Laser Patterning of High T_c Cu Oxide Films," preprint Nov. 87) have shown that this can be done by laser ablation with little or no degradation of the film properties. The film was 1.6 microns thick on sapphire. An excimer laser at 248 nm and a fluence of 0.86 J/cm^2 was used to ablate the film. Contact masks were used to define the pattern. Lines as narrow as 30 microns can be easily formed using a contact mask. The resistance as a function of temperature for the film was measured before patterning and for the line after patterning. Small differences between the two curves may be attributed to either non-uniformities in the film or the ablation process. The critical current density of this line was measured to a 500 A / cm^2 at 4.2 K. This low value is presumably due to the grain boundaries of the film.

The major advantages of laser ablation technique were twofold. First, the process is very quick, taking less than a minute to ablate a 1.6 micron thick film. Second, laser ablation requires none of the wet processing associated with conventional lithography. Thus the possibility of film degradation due to <u>chemical reaction is minimized</u>. Ablation has been successfully tried at wavelengths 0.308, 0.248, and 0.193 microns for patterning this material. The practical linewidth obtainable with this technique has yet to be explored but may be limited by the amount of melting which occurred at the edge of the ablated region. No attempt has been made to optimize the ablation conditions in this work. Smaller and more complicated structures can be patterned using projection techniques for pattern definition.

In conclusion, it has been demonstrated that high quality Y-Ba-Cu-O films can be sputtered from metal alloy targets. High sputter rate and good global homogeneity over a large area has been achieved. Laser ablation has been demonstrated to be a useful technique for patterning oxide films with no serious adverse effects.

To produce good DC-SQUID's, one needs submicron geometry definition. Unfortunately, due to the inhomogeneity of ceramic films and their instability when chemically attacked, the typical methods of photolithography may not be used. ARC suggests that the best method to produce the submicron "weak links" is to <u>modify</u> the chemical structure and/or crystallographic structure of the ceramic film, i.e., to destroy the superconducting phase in a submicron width across a few microns films produced by laser ablation.

ARC specializes in diverse aspects of radiation damage in superconductors. Recent data suggests that high T_c superconductors are quite sensitive to irradiation. The results of the group of F. Rullier-Albueque et al.(24)

suggests than an irradiation dose of 10^{10}e/μm^2 suppresses the superconductivity in La-Sr-Cu-O films. The damage rate is roughly twelve times larger than in similarly irradiated Nb_3Ge. Similar studies are being performed with Y-Ba-Cu-O films, and an even higher sensitivity is expected.

A comparable flux of electrons can be easily obtained in Scanning Electron Microscope. Thus, there exists the possibility of obtaining the submicron resolution weak junction <u>after</u> laser ablation steps. We believe that this new method of producing the weak junctions has a considerable advantage because it permits a very fine geometrical definition of the weak link and, by regulation of electron flux and energy, permits flexibility in defining the junction critical current and other superconducting properties.

2.0 THE ARC/NBS EFFORT

We proposed that in Phase-I we will concentrate on three major tasks:

A. Development of low-cost, user friendly DC-SQUID electronics;
B. Study of radiation damage in superconductors using scanning electron microscopy as a first step towards generation of submicron weak-links via scanning electron microscope;
C. Development of an x-y computer-driven laser deflector with micron spatial resolution and study laser ablation of ceramic films.

Diverse factors described below motivated us to concentrate in the Phase-I effort on the development of the low-cost, computer oriented DC-SQUID electronics. We believe our effort was quite successful and describe it in the Se$ions 3 and 4.

We divided the performance of task B into two subtasks:

B1) study of radiation induced modification in low T_c Josephson Junctions;
B2) study of radiation induced modification in 1-2-3 high T_c superconductor.

Task B1 was successfully accomplished in collaboration with the group of Prof. R. Huebner, Tubingen University. The brief description of our results is provided in Appendix 1.

ARC is fully equipped to produce the thin films of good quality Y-Ba-Cu-O films. However, the recent study of R. Koch, IBM, shows conclusively that Thallium-based films are superior to 1-2-3 compounds as a basic material for DC-SQUID production. Unfortunately, Thallium is very poisonous and the required safety enhancement in the ARC thin film facility could not be afforded within the Phase-I budget. The fabrication of Thallium based films and micropatterning using low temperature scanning microscope will be one of the optional tasks of Phase-II.

Task C assumed the coding of modified NBS-Boulder double transformer DC-SQUID geometry into the PC-driving the laser. This is a considerable effort which we decided to perform only after debugging the NBS-Boulder DC-SQUID design. Thus in the first two months of the project we carefully tested four DC-SQUID chips provided to us by the NBS group. Unfortunately, we found that that there are still some minor performance limitations, e.g. excessive 1/f noise and fragility of planar gradiometer. The next batch of DC-SQUID's were expected by the end of 1988. Unfortunately, the major fire in the photolithography room of NBS-Boulder had delayed our joint projects.

As described above, two major factors influenced the Phase-I program of ARC:

- major fire in photolithographic facilities of our collaborators in NBS-Boulder.
- shift in emphasis from 1-2-3 films to bismuth/thallium films as basic material for high T_c superconducting electronics.

Thus, we enhanced task A of our research program and we believe that the results justifies our decision.

3.0 DEVELOPMENT OF MULTICHANNEL DC-SQUID READOUT

We should like to mention three aspects in which existing DC-SQUID technology can be improved:

1. need of liquid helium;
2. price; and
3. the requirement of highly competent manpower to operate DC-SQUID's.

The need of liquid helium leads to systems which are expensive, require skillful operators, and are not portable. Thus, the development of LN_2 SQUID's is a necessary condition for more extensive use of this ultrasensitive technology. It is, however, a necessary but not a sufficient condition. In our opinion, the availability of LN_2 SQUID's forces us to redesign the electronic readout system, e.g. to make it cheaper and more "user friendly." In the following we describe some progress which is being made by ARC in this direction.

Commercially available DC-SQUID's are quite expensive, about $15,000-$20,000 per channel. In some applications four or more channels are required. However, when the application is well specified, which is the case in sensors readout applications, improvement of array performance and considerable economy is possible.

Finally, we should stress that the military applications of cryoelectronics requires systems which are:

- simple/reliable;
- remotely controlled;
- self-testing and self-calibrating;
- easy to interface with other electronics modules.

To meet these specifications, we designed/tested the multichannel DC-SQUID system, which can be digitally controlled. The schematics of the single channel is shown in Figure 1 and for clarity of future descriptions, it can be divided into three parts:

1. a ceramic film junction operating in LN_2 and coupled to the "real world" by a superconducting double transformer;
2. a low noise preamplifier; and
3. a phase lock-in amplifier.

3.1 SQUID Signal Conditioning and Digitization

The DC-SQUID consists (see Fig. 1) of the two weak links, one inserted in each arm of a superconducting ring of inductance (L_S) threaded by a flux (ϕ_S).

With an appropriate DC bias, the voltage (V_S) across the SQUID shows a periodic dependence on ϕ_S. When the applied flux causes V_S to be between the two extremes, the voltage is especially sensitive to the flux changes and forward transfer coefficient ($dV_S/d\phi_S$) displays a value as high as 20 $\mu V/\phi_o$, wherein $\phi_o = 2 \times 10^{-7}$ Gcm^2. Unlike RF-SQUID's, the DC-SQUID's are limited only by the intrinsic noise of the junction. They have been developed into devices with orders of magnitude with greater sensitivity than greater sensitivity than RF-SQUID's.

A negative feedback arrangement is commonly included to establish a flux-locked look and provide a linearized voltage output proportional to the

flux applied in the SQUID[14]. To improve sensitivity, a circuit tuned to the modulation frequency (f_m) is used to match the very low impedance of the SQUID to the higher impedance of the preamplifier. Two types of preamplifiers have been developed based on J-Fet's and bipolars. The first type is characterized by somewhat lower noise and can be operated at very low temperature (especially GaAs-Fet's). These have a very large input impedance, however, and considerable effort is required to build appropriate tank circuits. The bipolars type may have an input impedance as low as 300Ω, but cannot be operated in LHe, i.e., have a somewhat higher noise level. We believe, however, that the bipolar preamplifiers are the proper choice when LN_2 SQUID's are operated.

The typical values for the modulation frequency are on the order of 100 kHz, and the bandwidth of the tuned circuit permits observation of applied fields in the frequency range from DC to few kHz.

Finally, we should like to mention that the performance of SQUID's as sensors depend upon:
- the intrinsic noise of the SQUID;
- the efficiency of coupling to the external world;
- the noise of the first stage of preamplifier;
- the noise/reliability of phase lock-in;

The usefulness of DC-SQUID systems (especially in space-borne applications) is strongly enhanced by a possibility of computer operated DC-SQUID.

In the following, we describe:

1) development of low noise preamplifiers
2) development of phase lock-in;
3) computer interfacing of proposed system.

The periodic voltage versus flux characteristic of the SQUID presents three challenges to the readout electronics:

1. The high sensitivity of the SQUID imposes a limit on the total flux threading the SQUID loop to keep the same operating point. Thus, feedback must be used with the SQUID functioning as a null-detector.

2. The need to amplify signals down to DC in the presence of offset and drift both in the SQUID and in subsequent amplifiers makes operating the SQUID as a linear transducer impractical. Therefore, the SQUID can only be used in its nonlinear region as a low noise modulator whose output is then filtered, amplified, and fed back.

3. The amplifier must be fast enough to prevent unlocking yet have the lowest possible noise in order to take advantage of the sensitivity of SQUIDs. A block diagram of such a lock-in amplifier appears in Fig. 2. Our task at ARC has been to optimize it with respect to speed, noise, parts count and applicability. In particular, we have tried to match the performance of Berkeley's 1984 design.

4.0 First Prototype of DC-SQUID Electronics

Concerning low noise preamps we designed/implemented two preamps:

a) low noise bipolar preamplifier;
b) low noise Si-Fet based preamplifier;
c) very low noise cooled GaAs-Fet based preamplifier.

The development of a low noise bipolar preamplifier is described in Appendix 2. The Si-FET based preamp is a modification of preamps used by the Berkeley group and was described previously.

We pointed out that the phase lock-in amplifier used in SQUID signal conditioning is the most expensive part of the readout electronics. Furthermore, this electronics was designed for single channel operations. Typical phase lock-in amplifiers have a few ten-turns potentiometers, a series of switches and analog output, it is not overly complicated but definitely not a "user friendly" system. We believe that one can redesign the lock-ins to:

- considerably decrease price/channel;
- provide a "user friendly" computer oriented system compatible with NIM and IEE-488 standards.

ARC is currently testing such a more versatile multichannel system. Our preliminary CAD/CAM study suggests that we can develop a multichannel system with a target price of about $2,000/channel. Each channel will be housed in a single width NIM module and the analog signals will be digitized by 12 bits ADC. Most probably we will use CAMAC-based ADC's and computer control via IEEE-488.

As a first step in the development of computer oriented multichannel DC-SQUID's we implemented:

a) flux counter/interface to computer;
b) low-cost lock-in amplifier.

The development of the flux-counter is relatively straightforward. The main considerations were reliability and ease of interfacing to personal computer. The design is discussed in Appendix 3. This device has been developed in collaboration with UBC, Vancouver and was quite successful; it was used continuously for a few months in a series of physical experiments (Development of Superconducting Granular Detector). More specifically, we used commercially available LabNote software for data acquisition. The system was implemented on IBM-XT clone.

The development of prototype lock-in amplifers have the following motivations:

a) develop cheapest possible lock-in amplifier appropriate for DC-SQUID readout;
b) study the possibility of interfacing this prototype to diverse DC-SQUID sensors;
c) study reliability and ease of operation in long term runs.

The first task was very successfully performed by N. Cao, ARC. A breadboard of a lock-in amplifier using six low noise I_C chips was built and compares favorably with the 1981 and 1984 Berkeley designs (see Table 3). The estimated cost for such a design is $500 (Table 4). We have slightly better noise than Berkeley 1984 readout along with diminishing the number of parts, cost and size. The design and laboratory tests using sensors produced by NBS, Boulder are described in Appendix 4.

Our group has available three types of DC-SQUID sensors:

a) produced by the group of M. Cromar, NBS-Boulder (both in PbAu alloy and more recent Nb sensors);
b) commercially available DC-SQUID sensors from BTI, Inc.;
c) experimental digital DC-SQUID from one of the German groups.

The prototype of DC-SQUID readout electronics was shown to be very versatile: we easily locked in to all the above mentioned sensors. The tests of the NBS-Boulder sensor is described in Appendix 4. The tests of BTI, Inc. sensors using three types of readout electronics are described in Appendix 5.

The reliability and user friendliness of our prototype were tested by the group at UBC, Vancouver. Unfortunately, they discovered some grounding problems and suggested modification. Furthermore, the performances of two DC-SQUID sensors produced by NBS-Boulder were considerably below both specifications and tests performed in ARC; actually one of the sensors died during transportation. The recommendations of UBC group/results of tests are enclosed as Appendix 5.

The above described developments were taken into account in the design of an improved, more user friendly version of DC-SQUID readout electronics.

5.0 The DC-SQUID Readout Electronics and Computer Interface

The first prototype of ARC SQUID electronic readout was tested with several DC-SQUID sensors (see Appendixes 4 and 5). On the base of the above tests, new, improved electronic readout and computer interface were designed; the analog part of electronic readout was assembled and tested with both NBS and BTI DC-SQUID sensors. The excellent noise of $1.6 \times 10^{-5}\phi_0/\sqrt{Hz}$ was observed. The digital part of electronic readout was partially built; and for remaining digital parts of electronic readout and computer interface we have complete design. It will be assembled/tested in June 1989. The SQUID readout consists of three main blocks (see Figures 3 and 4):

1. FET preamplifier and current drivers - Figures 5a and 5b,
2. lock-in amplifier and feedback control systems - Figure 4,
3. digital control system and computer interface - Figure 14.

The first block (see Figures 4 and 5) is assembled as separate units in a compact box and is placed on the liquid helium/nitrogen cryostat in the vicinity of SQUID sensor; shielding has been greatly improved in comparison with the first prototype resulting in substantial decreasing of cross-talk between modulation signal and preamplifier. Current drivers of LC filters have been added to diminish sensitivity to external electric noise. In addition the connection between preamplifier/drivers box and lock-in amplifier has been improved by the use of multiconnector coax connector to improve shielding and facilitate assembly/disassembly.

The basic elements of the second block - lock-in amplifier and feedback control system - with one exception (see below) are similar to the first prototype - see Figure 4. The main effort was made to improve shielding between modules (oscillator - Figure 6, bandpass amplifier - Figure 7, phase sensitive detector - Figure 8) and to allow <u>digital control of diverse functions</u>. In particular the analog controls of bandpass amplifier gain, system bandwidth (feedback amplifier), integration time, coarse demodulation phase, output filter bandwidth, offset regulation and reset have been replaced by digital/computer suited control subsystems - see Figures 9, 10, 11, 13, 12, and 14. The improvements in control systems make the operation of SQUID electronic readout easier and improved the versatility of the readout and facilitates adaptation of the electronic readout to different SQUID sensors and to different matching circuits.

The phase detector used in the present readout system is different than the one used in the first prototype. In place of multiplication circuit, a MOS FET switch is used as a phase sensitive decoder (Figure 6). Preliminary noise spectrum measurements suggests that the new decoder exhibit lower noise at low frequencies.

The third block - digital control and computer interface has been only partially built. All blocks directly controlling the analog part of the readout system have been built and tested (see Figures 4, 8, 9, 10, 11, and 12). The automatic reset, improved version of flux counter, new (interrupt driven) computer interface and digital circuits necessary to maintain long term stability of reference level have been designed (see Figures 15 - 20) but still not implemented.

All digital circuits have been designed so as not to generate any switching noise during normal operation of analog part of the SQUID readout. That required that all digital signals are static unless operations like automatic reset, scale change, automatic zeroing, etc. are in progress. The above design concept will completely eliminate noise generated by digital control systems. However, the digital controller designed according to that concept is somehow complicated (see Figure 14 - 18). Some simplification of the digital control will be possible in multichannel systems because all controller circuits with the exception of the DAC board (Figure 17) can be common for several SQUID readouts.

The alternative concept of digital control is being designed; it is made possible by the immunity of our DC-SQUID electronics to the high frequency noise and computer generated noise (see Fig. 19). Thus, noise is not a critical parameter of the system, e.g. when using operating DC-SQUID sensors in liquid nitrogen, the simpler controller and computer interface can be possibly used. The design of alternate controller is based on the use of commercial multichannel ADC/DAC/digital input-output cart for IBM-PC type personal computer. This type of digital interface was developed by ARC/UBC group for BTI RF-SQUID. We are currently implementing a similar interface for our DC-SQUID electronics. The Data Translation DT2805/5716A care is now under tests; it will be used to drive the digital blocks directly controlling analog readout. These blocks (already tested) will be used as buffers to decrease influence of digital noise generated inside computer on analog readout. The advantage of the use commercial cart in place of a dedicated controller is that the controller is realized as software in place of hardware. The digital controller software can be made more flexible than hardware one and because the use of the commercial parts in place of dedicated ones will be much less expensive. We will test these two controllers in the summer of 1989. A final version will be tested before the end of the year.

6.0 SUMMARY

The main effort of ARC/NBS in Phase I has been concentrated on the following tasks:

1. Study of possible technique of production of high T_C SQUID sensors,
2. Constructing and testing of low cost, computer controlled multichannel readout system for DC-SQUID sensors.
3. Preliminary study of new, high resolution magnetic readout for focal plane detectors in IR/visible energy range.

In the first task, the applicability to high T_C superconductors of a new technique of controllable production of weak-link junctions by irradiation has been studied. It has been concluded on the basis of results of Tubingen University group that the irradiation technique connected with implemented in situ scanning electron microscopy process control allows production of a weak-link junction in a reproducible manner. This technique will be implemented in Phase II (if granted).

In the second task, the two different prototypes of DC-SQUID electronic readout have been built and tested with several SQUID sensors. Modular, multichannel, how cost, computer oriented electronic readout systems have been designed and partially constructed. Electronic readout was designed that way so that it can be configured according to different performance/cost requirement. Electronic readout is capable of remote control operation including data acquisition, calibration, resetting and zero adjustment. Only when a SQUID sensor is replaced by a new one is fine tuning by the operator necessary. In Phase II (if granted) a system capable of automatic adjustment to SQUID sensor characteristics will be constructed.

In the third task, the application of SQUID and Josephson junction based magnetic flux sensors for constructing a new magnetic readout system for multichannel plate photomultipliers has been proposed. The preliminary calculations suggest that a resolution of 10^4 x 10^4 can be achieved with only several sensors. Taking into account the unbeatable sensitivity of multichannel plate photmultipliers in IR and visible spectral ranges, the new readout system is suitable for constructing a detector with extremely high sensitivity and with a very high spatial resolution. Because of the importance of applications of such superior sensing system, we propose in Phase II (if granted) to use a multichannel SQUID system for experimental study of maximal spatial resolution possible to achieve with the proposed magnetic readout system.

Table 1: Performance Comparison of SQUID Lock in Amplifiers

Parameter	Notation	Berkeley 1981	Berkeley 1984	ARC
loop gain cross over frequency (KHz)	f_{cR}	.016	2.0	1.0
open loop slew rate (v/ms)	$\frac{d_{vol}}{dr}$	.5	50	50
Transient response		τ=10ms	photo 1	photo 2
Output signal to noise (dB)	$\frac{V_{out}}{V_{nout}}$	24	11	11
Equivalent noise input $(\mu V/\sqrt{Hz})_{RMS}$	$\frac{V_{nout}\beta}{6\sqrt{f_{cR}}}$	14.5	17	15

b) Lock-In Amplifier (Prototype I)

Part	DC-SQUID Readout Cost ($)/channel
Multiplier	$ 90.00
OP AMPS (low noise)	50.00
Capacitors	10.00
Connectors	40.00
Potentiometer (10 turns)	40.00
Power Supply	65.00
Hardware	50.00
Mounting	50.00
Total	$395.00

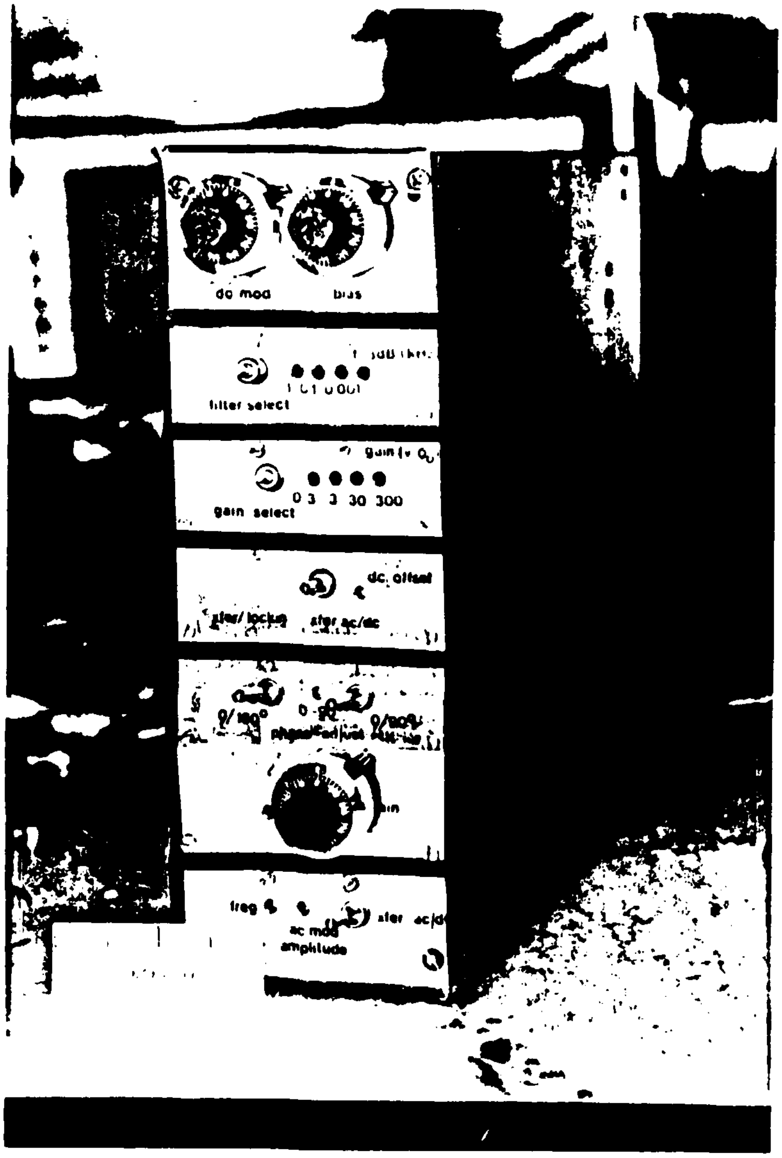


Photo 1a: ARC Dc-SQUID readout electronics (2nd prototype) : Lockin Amplifier/Computer interface module.

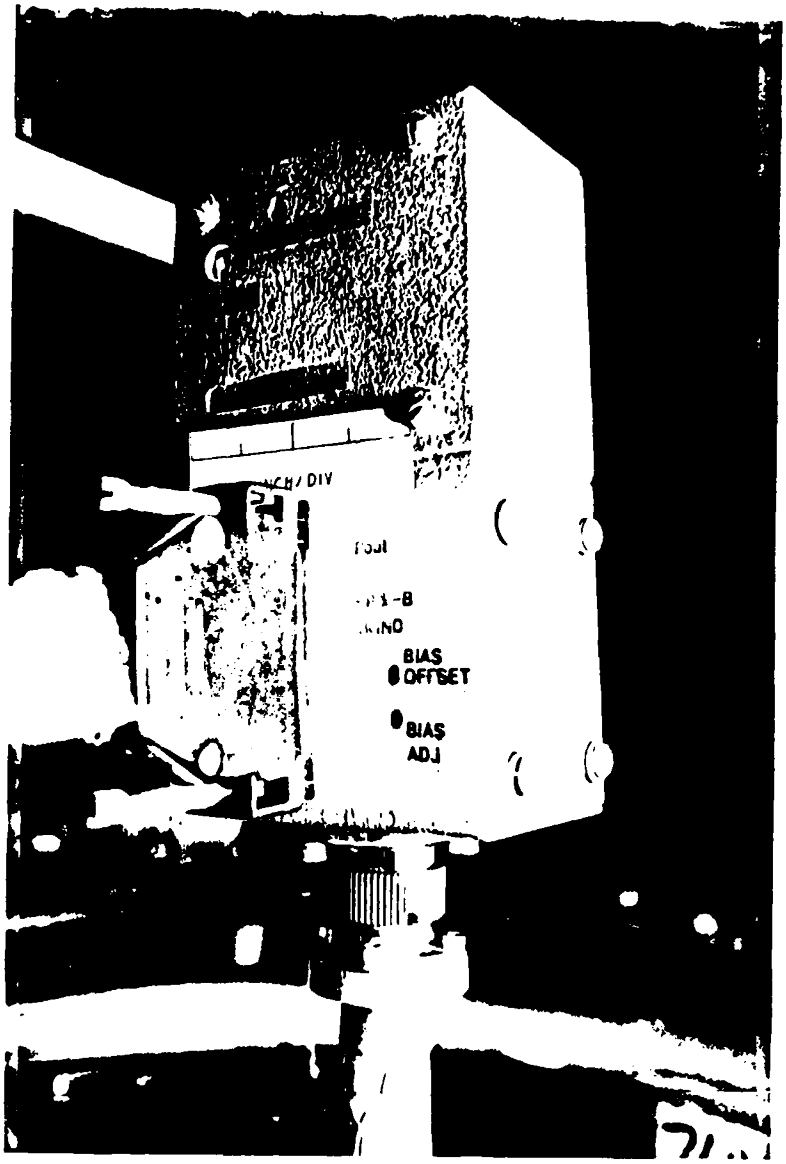


Photo 1b : ARC Dc-SQUID readout electronics (2nd prototype):
Preamplifier and DC-Squid probe.

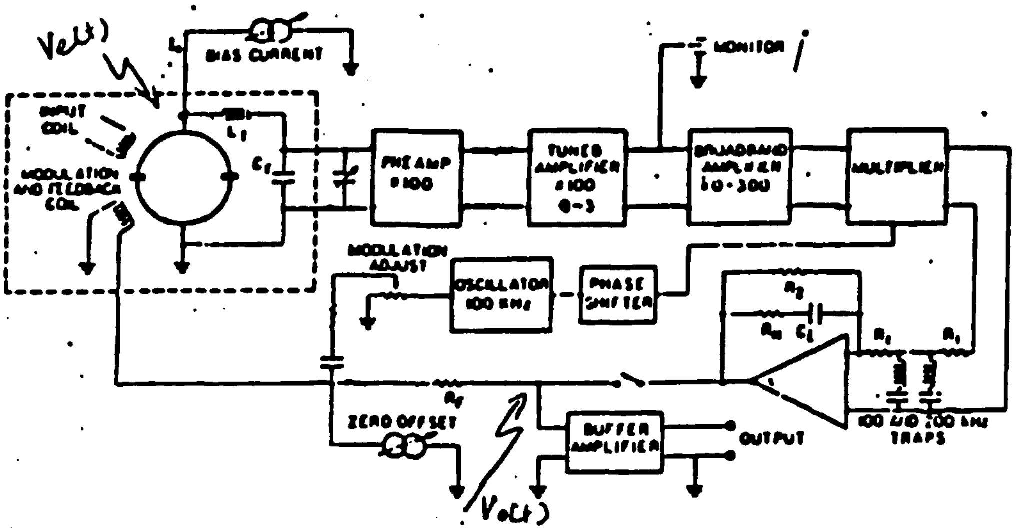
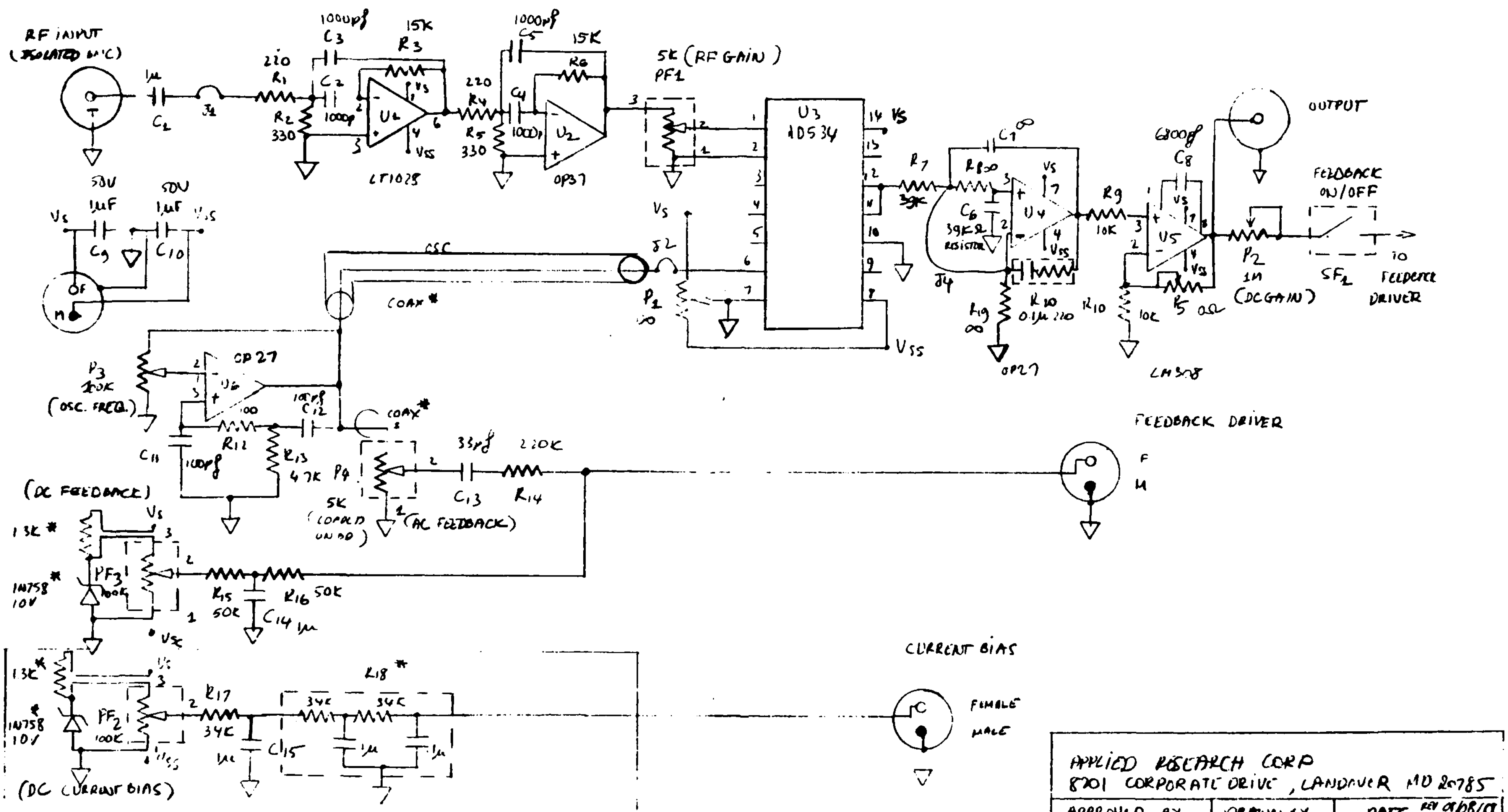


Fig.1. Schematicof the SQUID electronics.Components within the dashed box are at liquid helium temperature (Courtesy UC Berkeley)



NOTE
1 - ALL POTS ARE 10 TURNS AT LEAST
2 - ALL RESISTORS 1% METAL FILM, ALL CAPACITORS ARE CERAMIC
3 - ALL TWINAX ARE INSULATED FROM PANEL (SHIELDS SHORTED TO MALE PIN)
4 - ∞ MEANS NOT LOADED
5 - * JUMPERED ACROSS CUT TRACK

FIG-2

APPLIED RESEARCH CORP 8701 CORPORATE DRIVE, LANDOVER MD 20785		
APPROVED BY NGA CAD	DRAWN BY NGA CAD	DATE REV 01/08/88 06/27/88
SQUID READOUT (SCHEMATIC) WITH FET PREAMP		
DRAWING NO S0015	SHEET NO S	

... 78% reduction, legal size ...

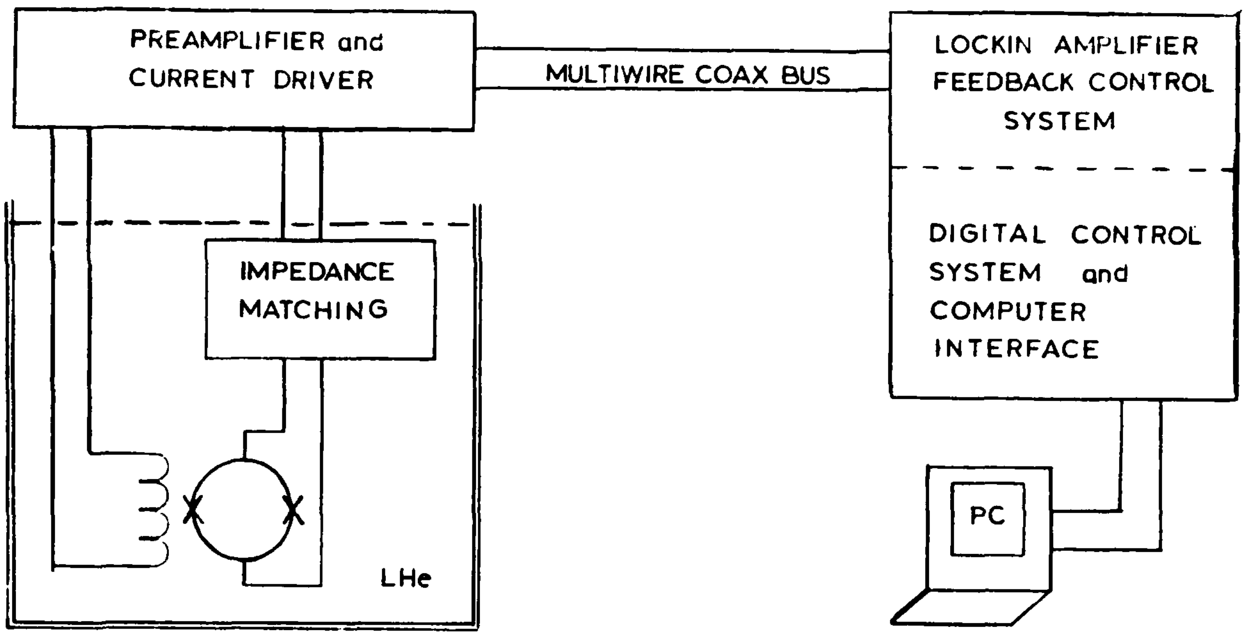


FIG-3 Block diagram of ARC SQUID electronic readout system.

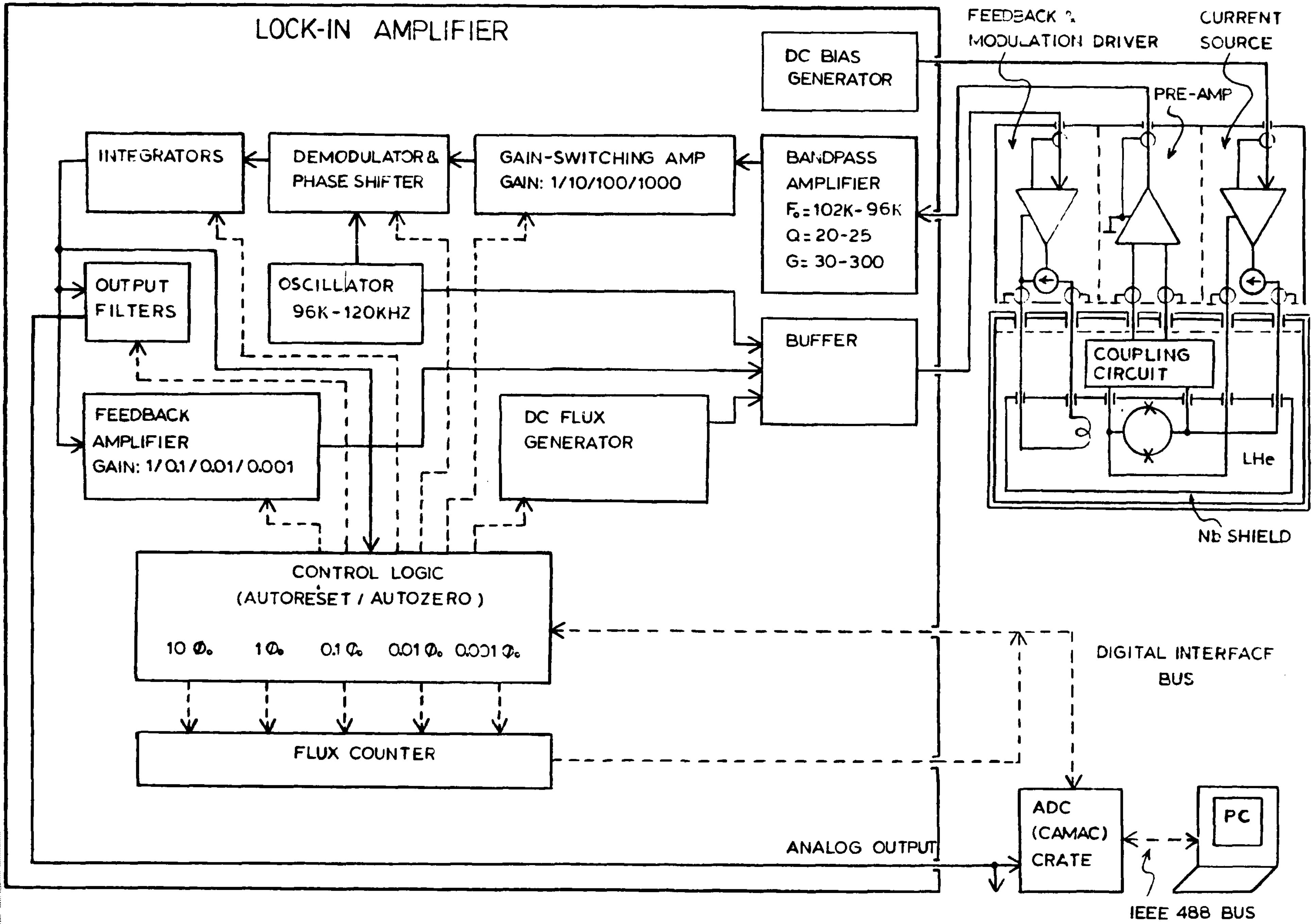


FIG-4 LOCK-IN AMPLIFIER AND FEEDBACK CONTROL FOR DC SQUID

PREAMP

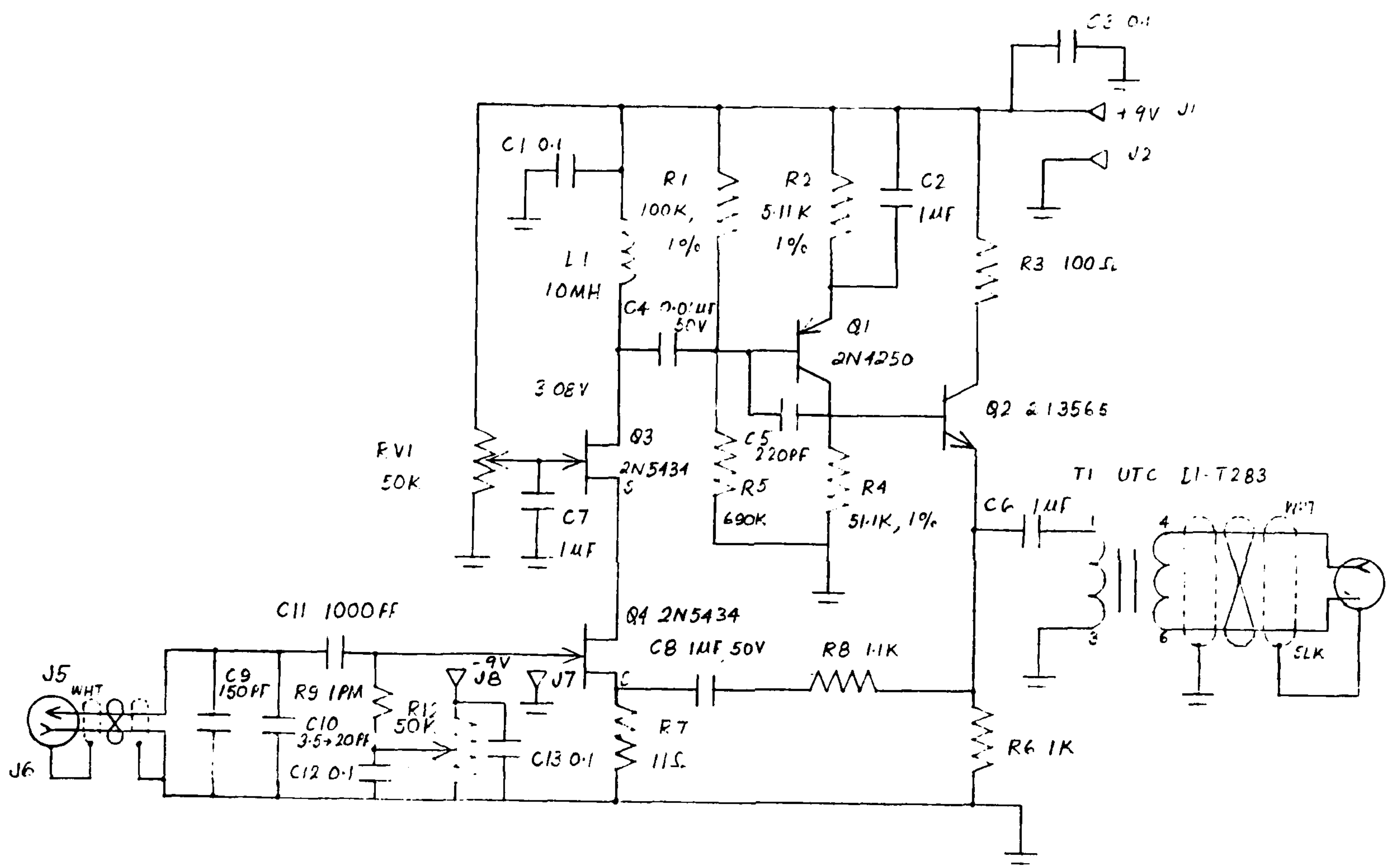
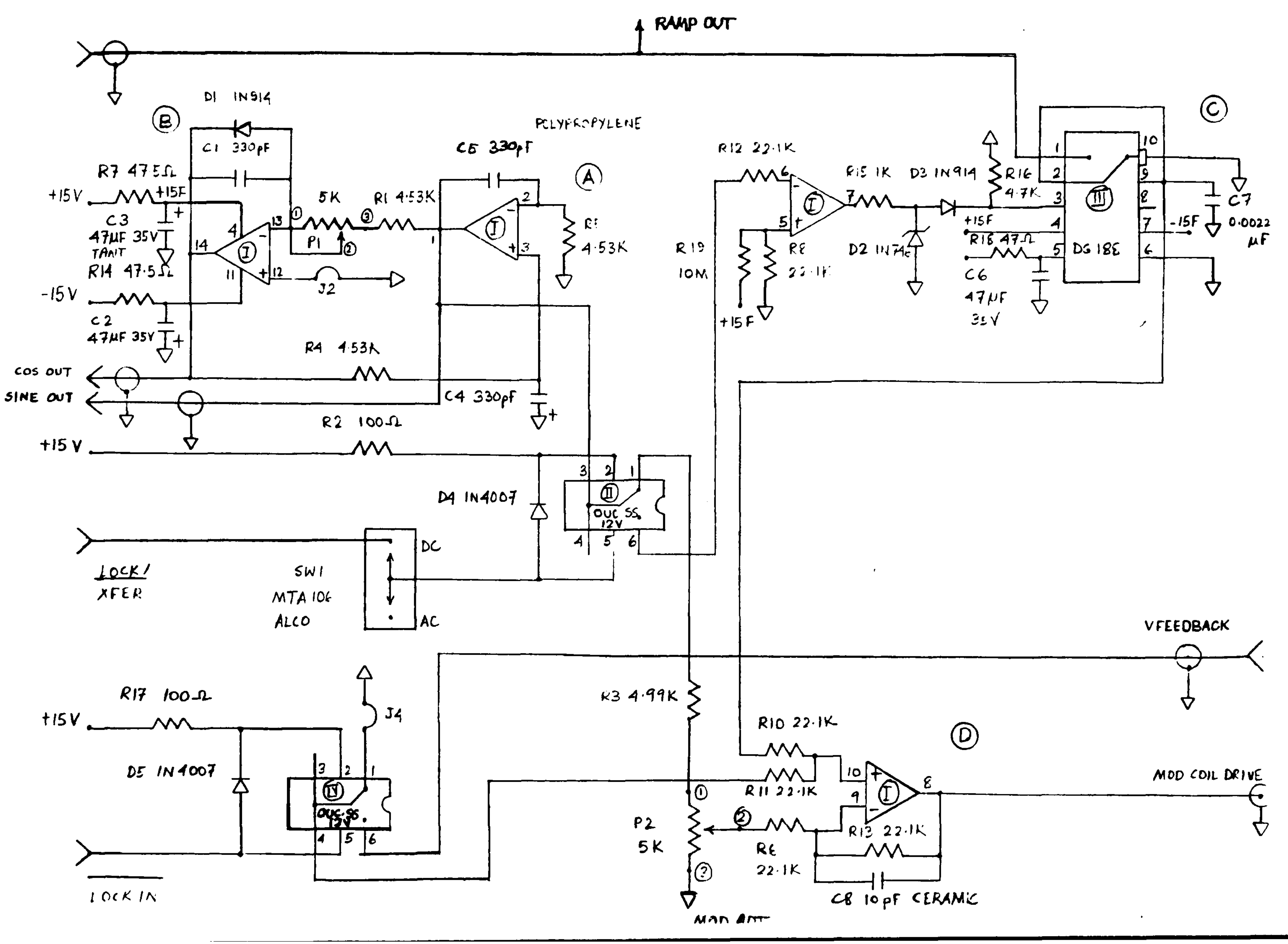


FIG 5a

REVISED:		
PREAMP UCBERKELEY (FET)		
SCALE:	APPROVED BY: N. CAO	DRAWN BY: R.A MAULA
DATE: 4/27/85		REVISED:
APPLIED RESEARCH CORP, LANDOVER, MD		

FIG-6 OSCILLATOR & DC/AC BUFFER



BANDPASS AMPLIFIER

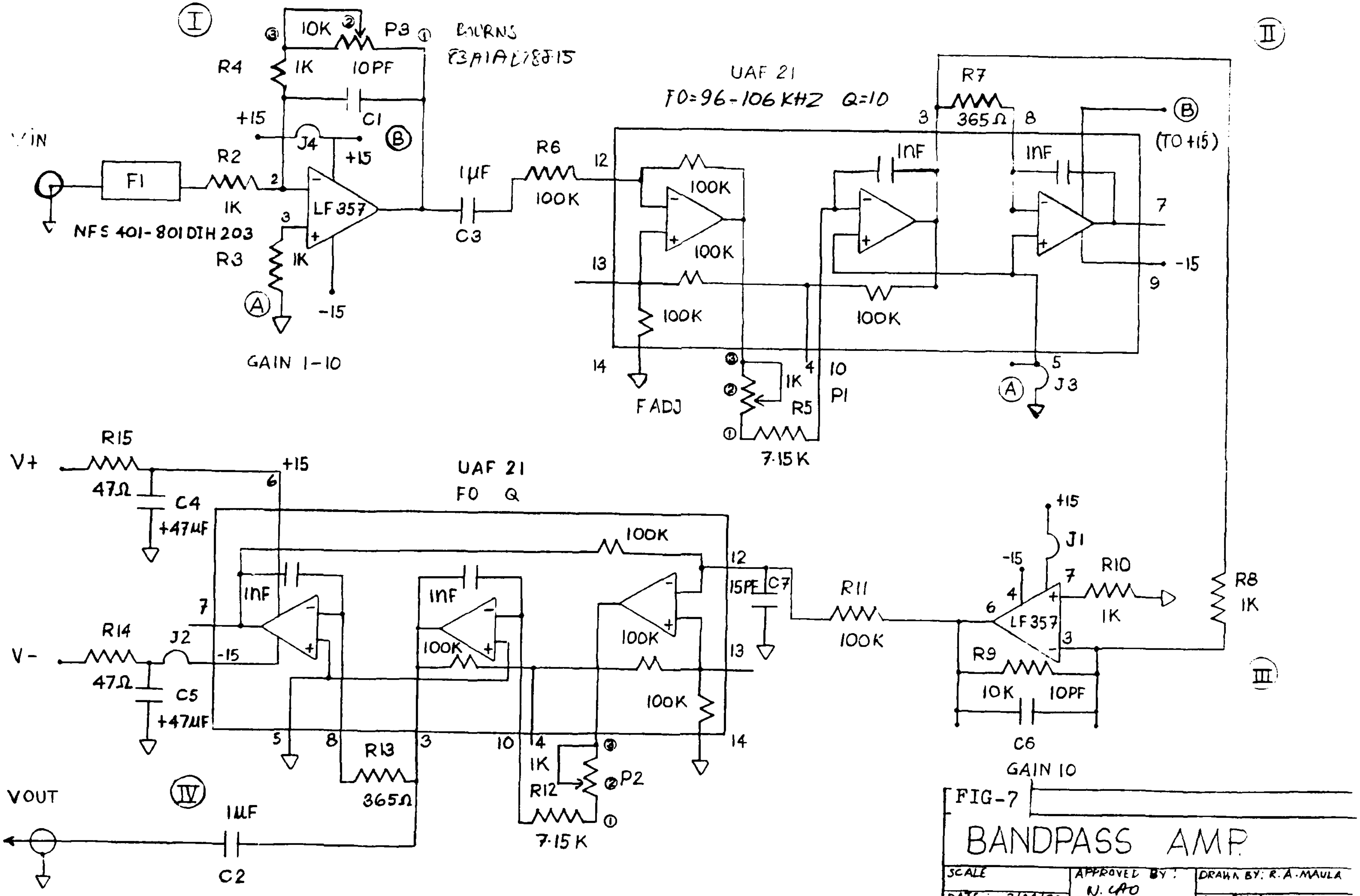


FIG-7

BANDPASS AMP

SCALE	APPROVED BY: N. CAO	DRAWN BY: R. A. MAULA
DATE 3/24/89		REVISED
APPLIED RESEARCH CORP, LANDOVER, MD		
ELECTRONICS SHOP		DRAWING NO:

DEMODULATOR

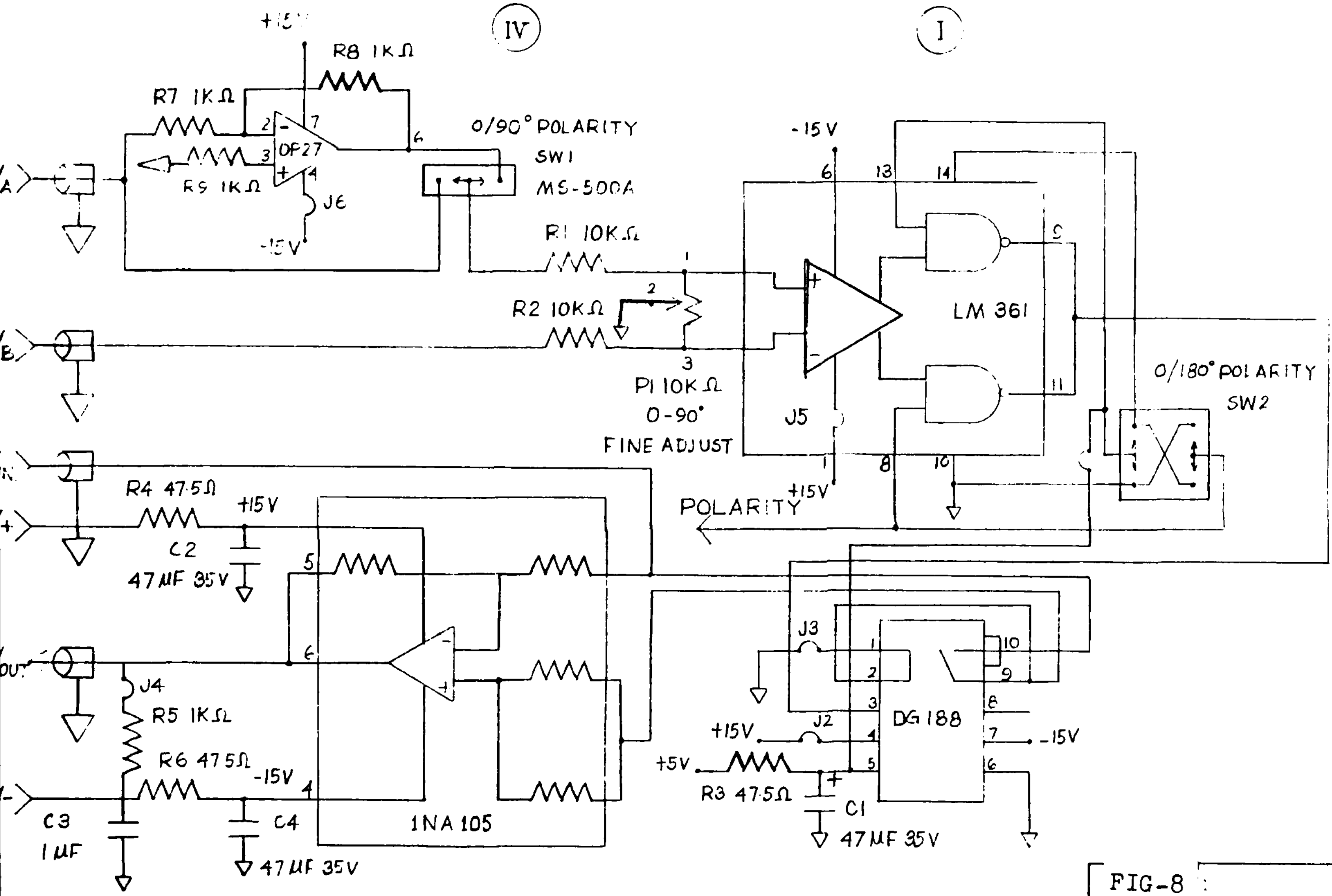


FIG-8

DEMODULATOR [GAIN 0.5]		
SCALE:	APPROVED BY:	DRAWN BY: R. MAUL
DATE: 04/05/89		REVISED:
APPLIED RESEARCH CORP, MD		
ELECTRONICS SHOP		DRAWING NO: 7:4[illegible]

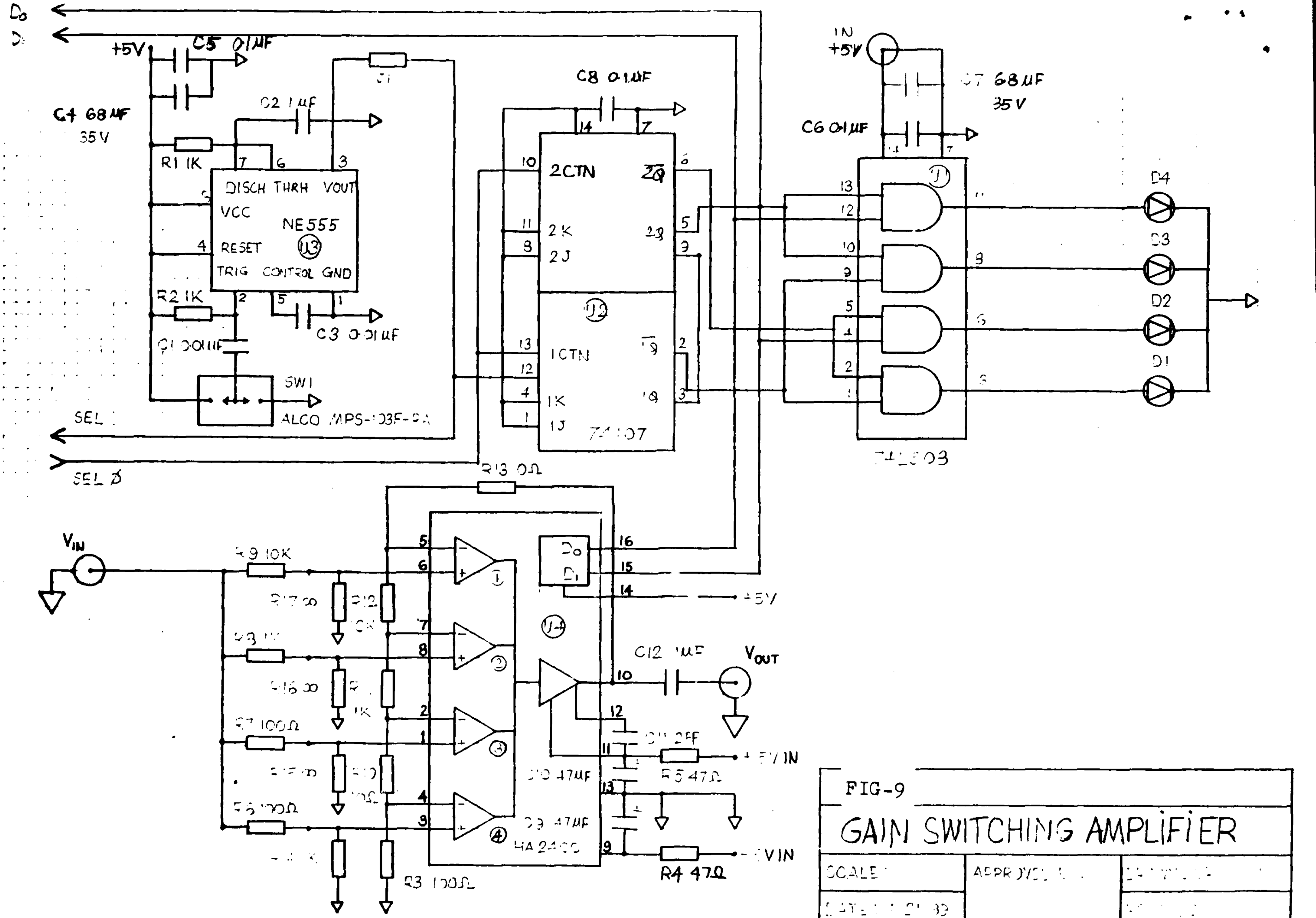


FIG-9

GAIN SWITCHING AMPLIFIER

APPLIED RESEARCH CORP. LANDOVER, MD

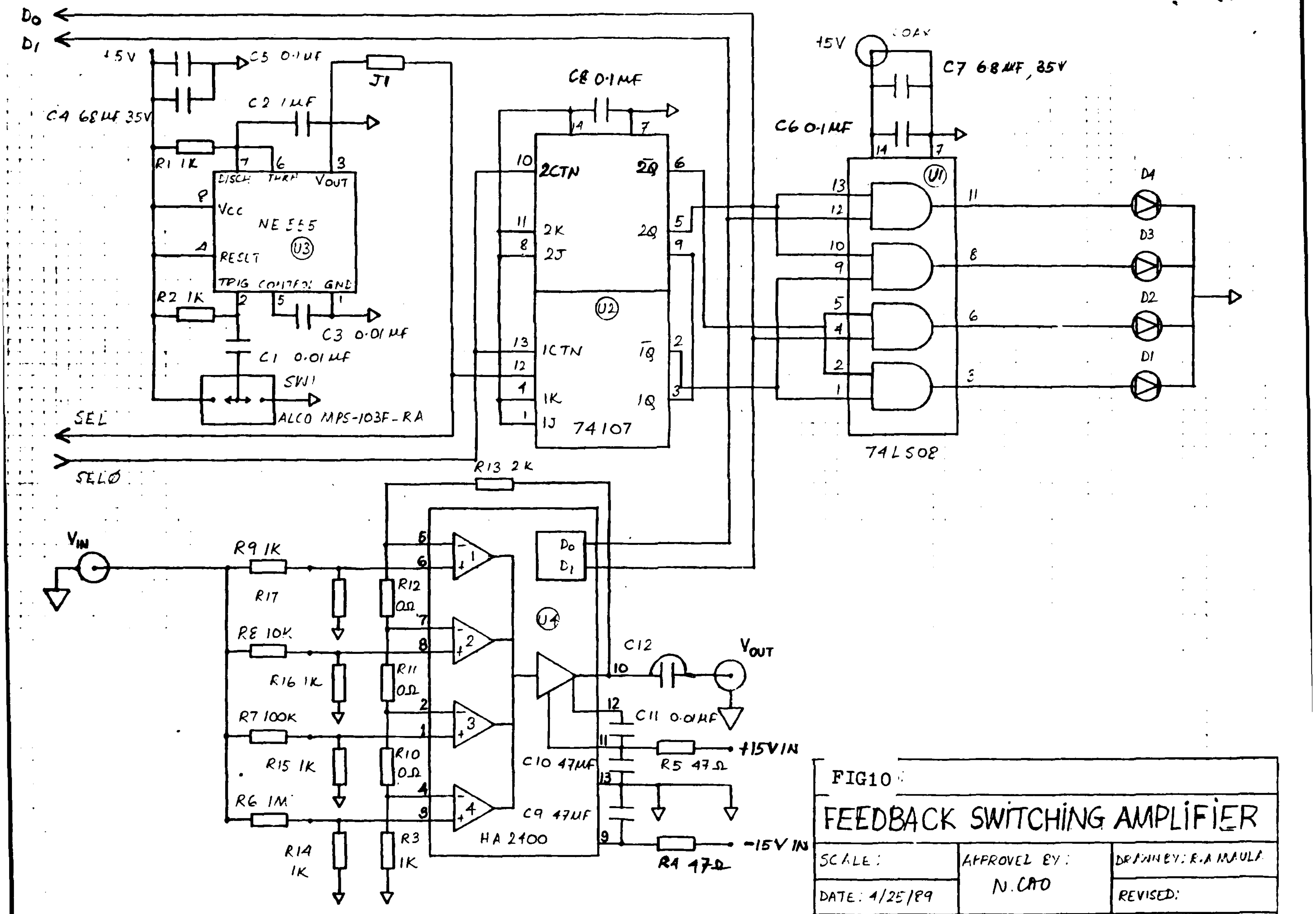


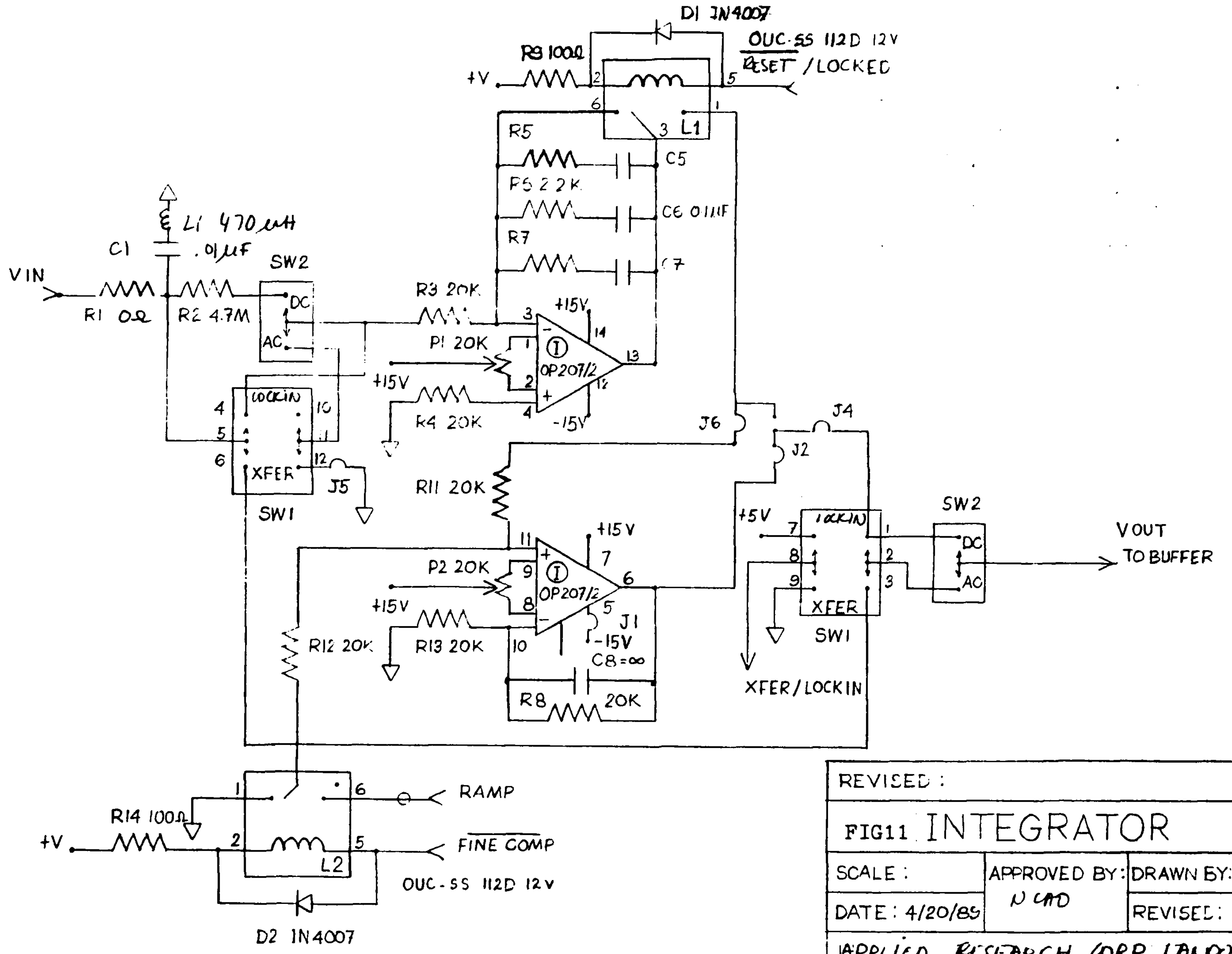
FIG10

FEEDBACK SWITCHING AMPLIFIER

SCALE:	APPROVED BY: N. CAO	DRAWN BY: R.A MAULA
DATE: 4/25/89		REVISED:

APPLIED RESEARCH CORP, LANDOVER

INTEGRATOR



REVISED :		
FIG11 INTEGRATOR		
SCALE :	APPROVED BY: N CAD	DRAWN BY: R.A. MAULA
DATE : 4/20/85		REVISED :
APPLIED RESEARCH CORP, LANDOVER, MD		
ELECTRONICS SHOP		DRAWING NO

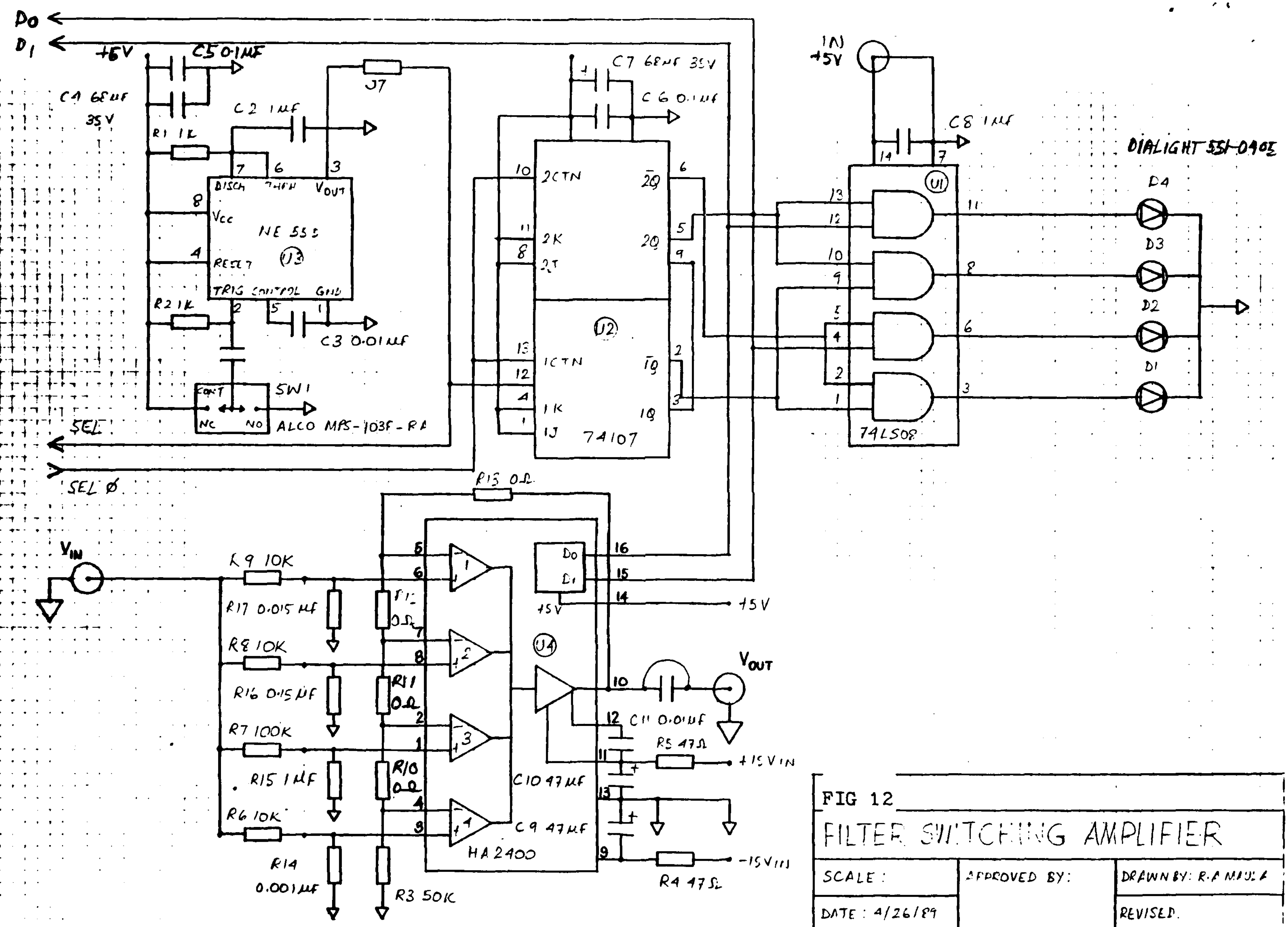


FIG 12

FILTER SWITCHING AMPLIFIER

SCALE:	APPROVED BY:	DRAWN BY: R.A MAULA
DATE: 4/26/89		REVISED:

APPLIED RESEARCH CORP, MD

DC BIAS / MODULATION

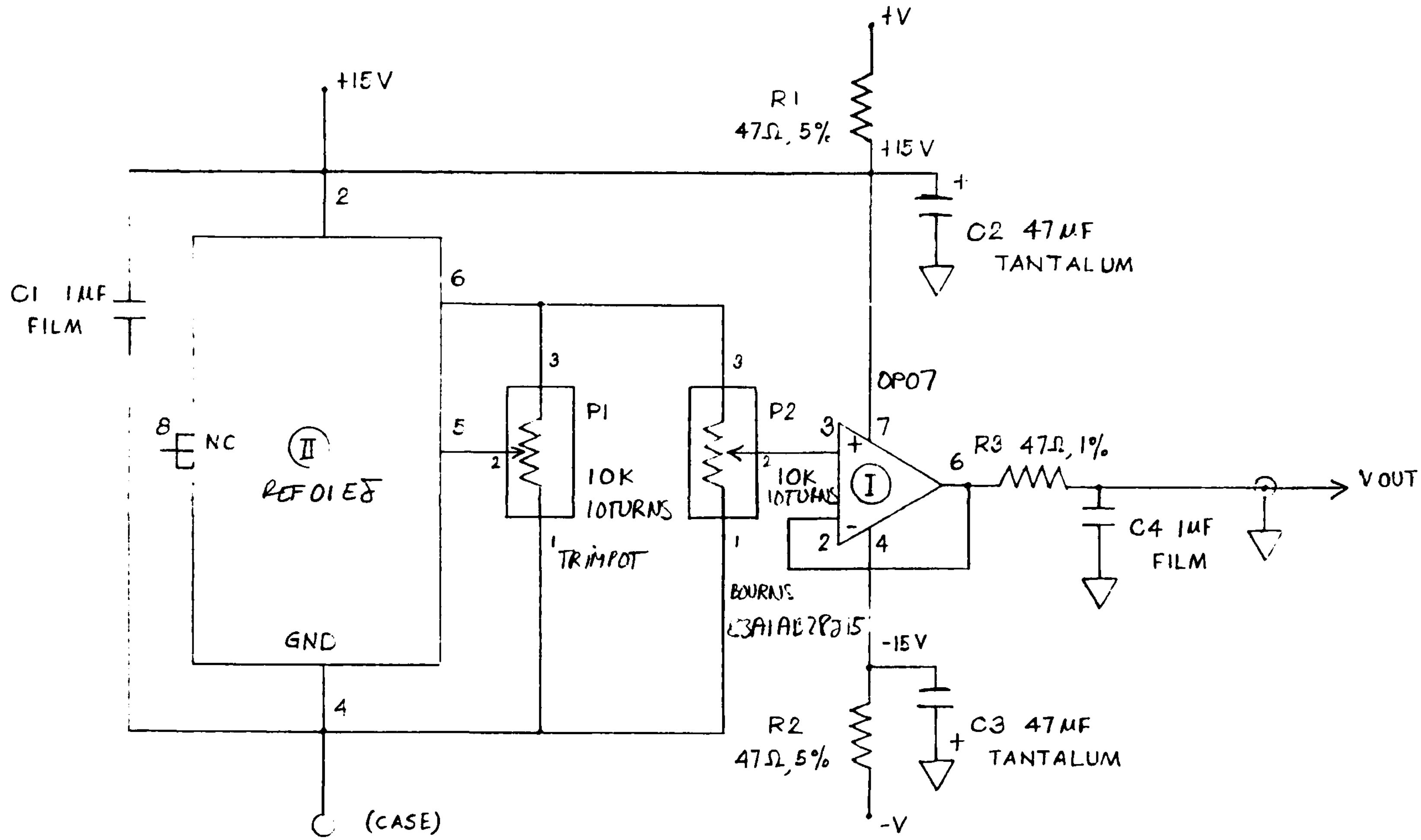


FIG-13		
DC BIAS / MODULATION		
SCALE:	APPROVED BY:	DRAWN BY: R.A. MAUL
DATE: 4/18/89		REVISED:
APPLIED RESEARCH CORP, MD		
ELECTRONICS SHOP		DRAWING NO

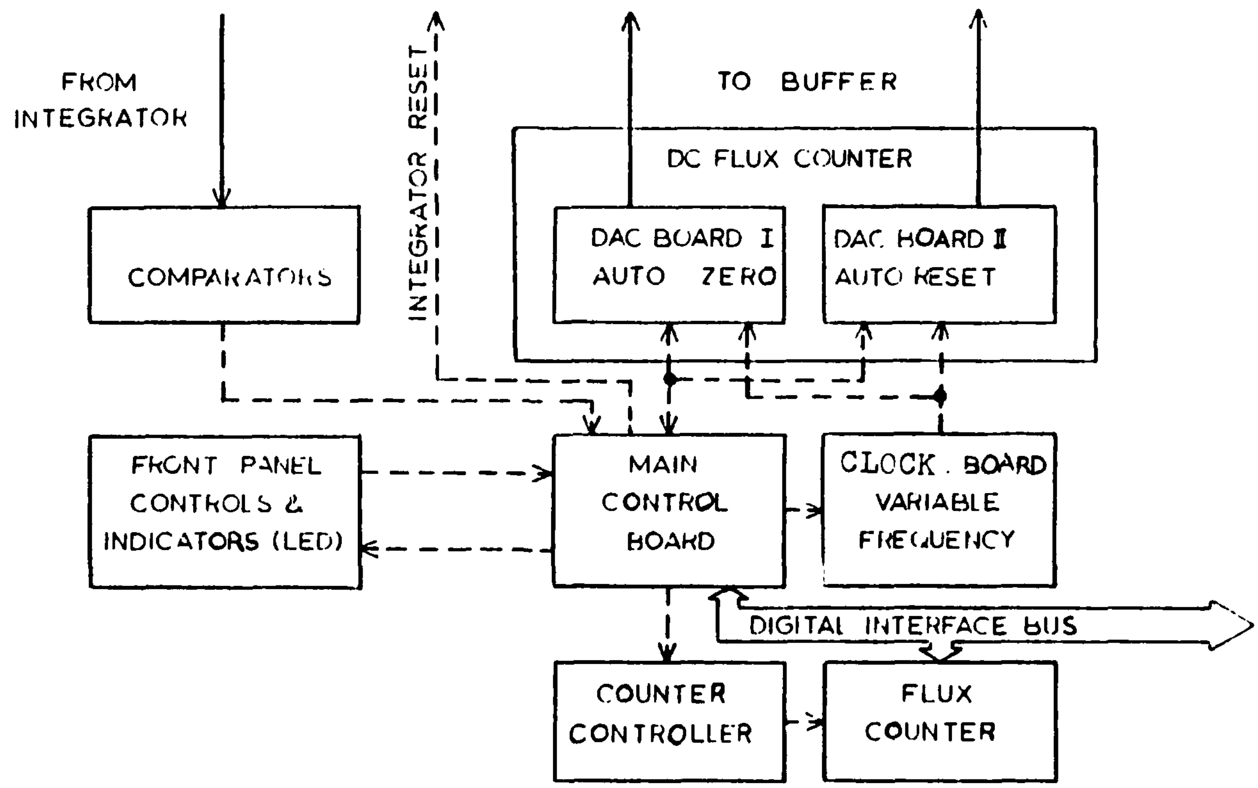


FIG-14 Control Logic .

FIG-15 MAIN CONTROL BOARD

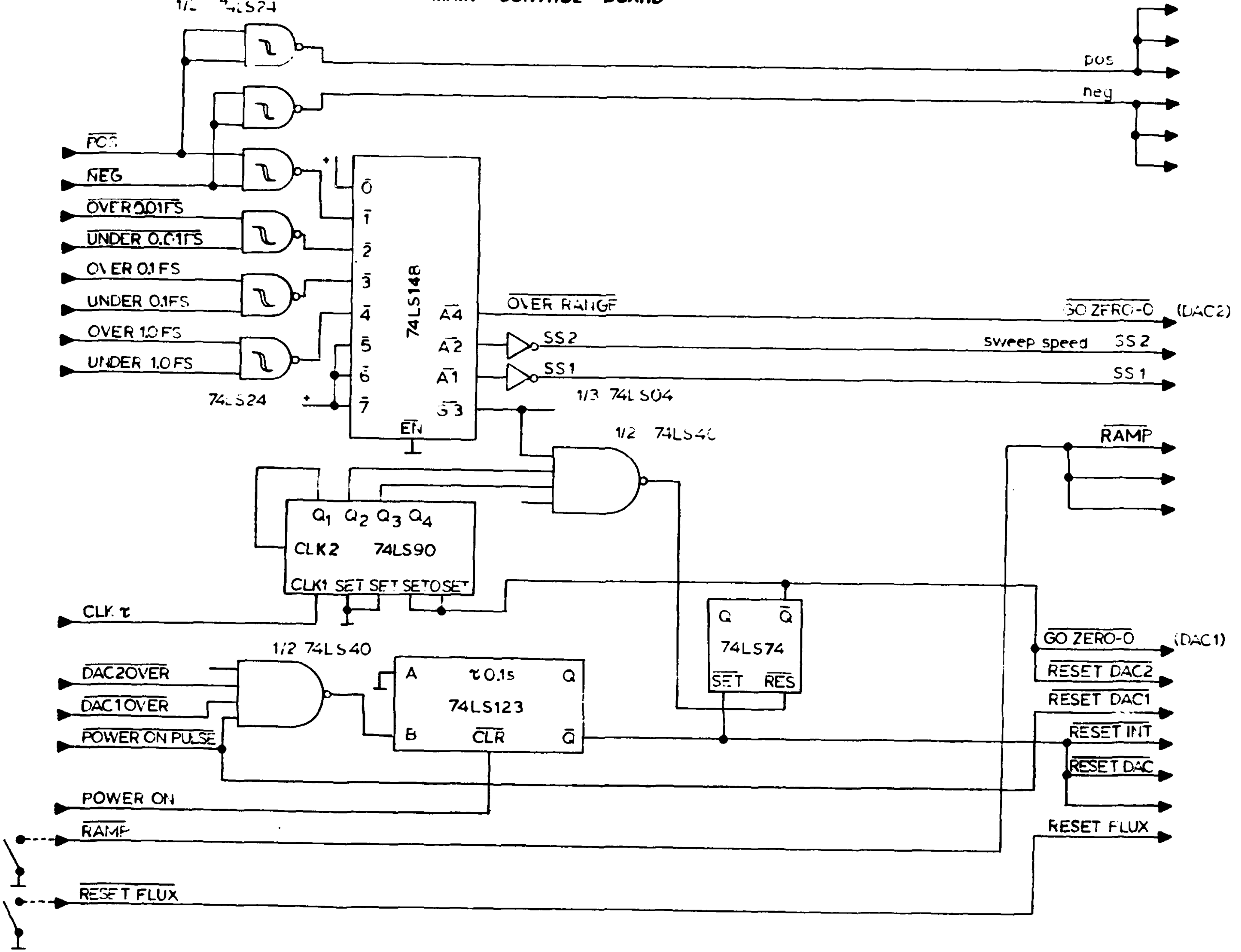
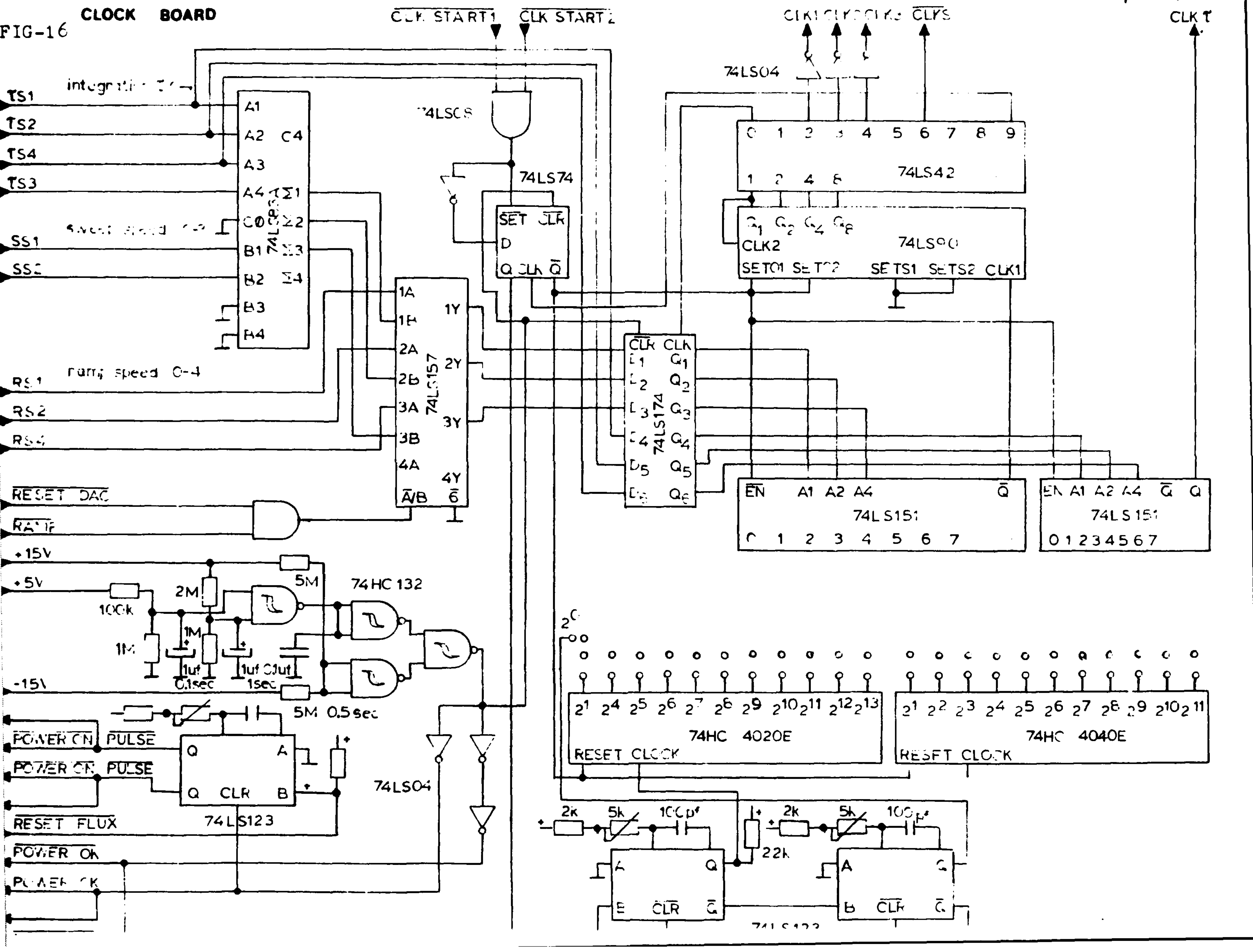


FIG-16



CLOCK BOARD
TS1
TS2
TS4
TS3
SS1
RS2
RESET DAC
+15V
+5V
POWER ON PULSE
RESET FLUX
POWER OK
74LS04
74LS74
74LS157
74LS174
74LS42
74LS151
74HC 132
74HC 4020E
74HC 4040E
74LS123
RESET CLOCK
CLK START1
CLK START2
CLK T
100k
2M
1M
5M
5M 0.5 sec
2k
5k
22k

FIG-17 **DAC BOARD**

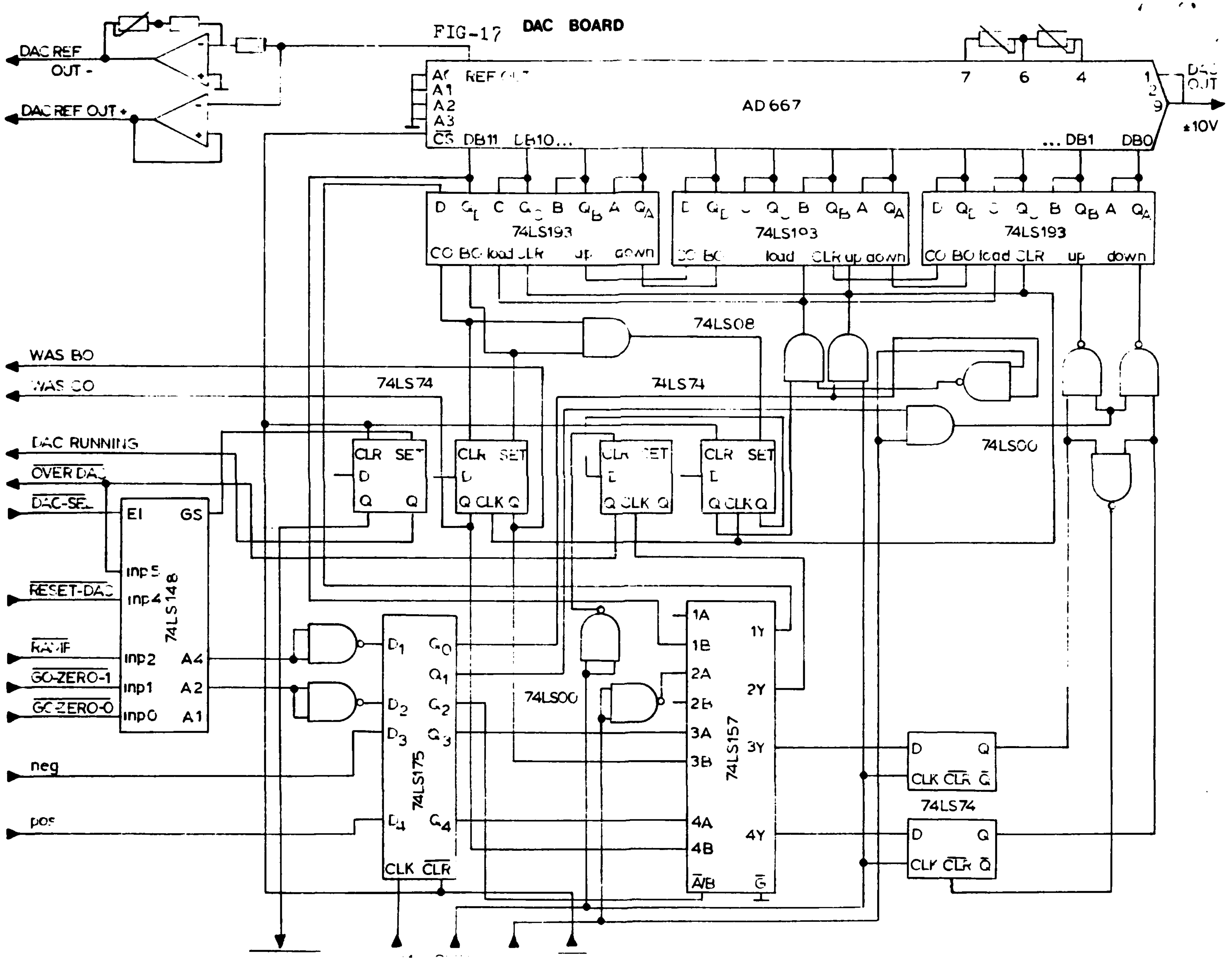
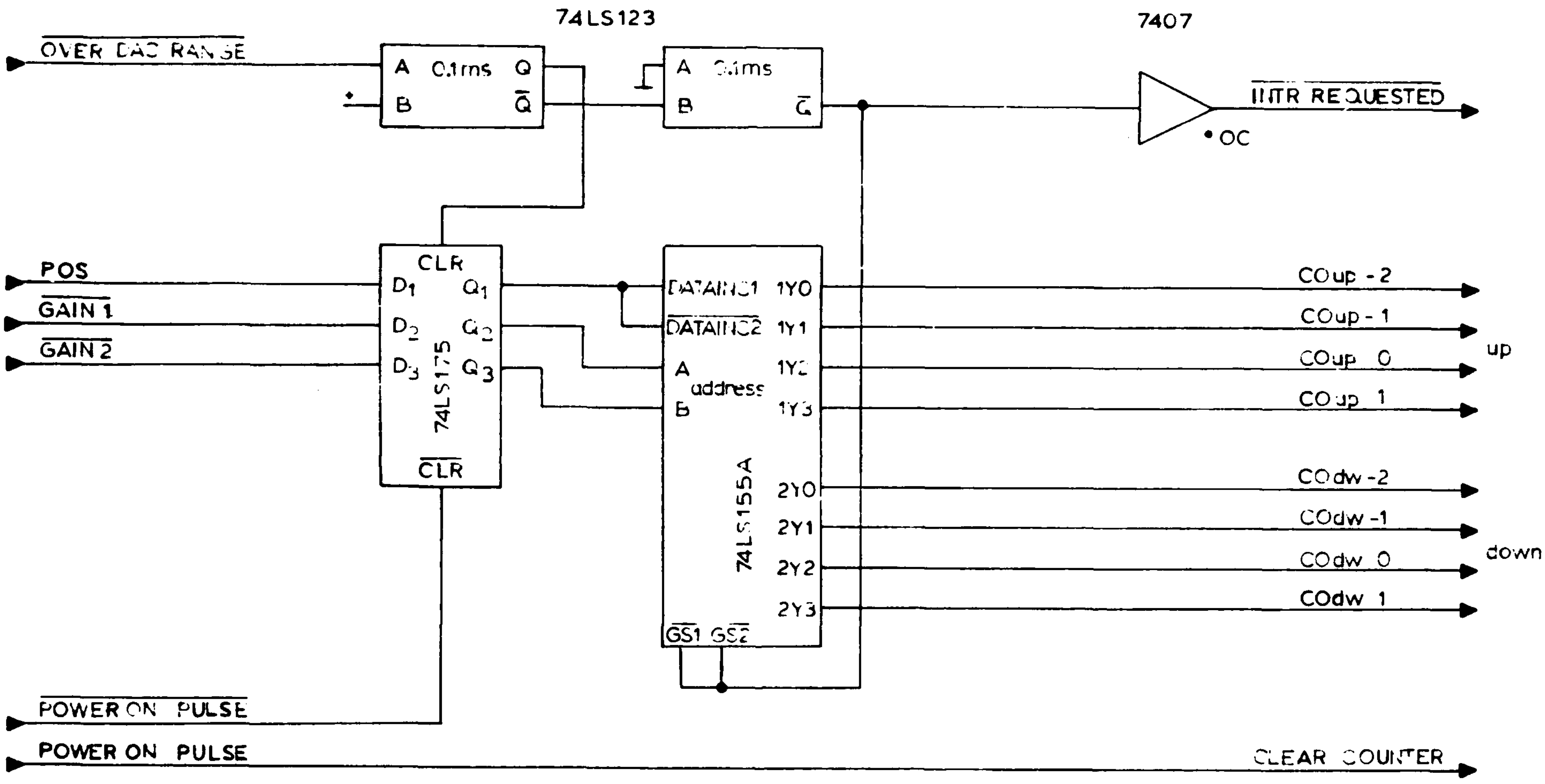


FIG18 **COUNTER CONTROL**



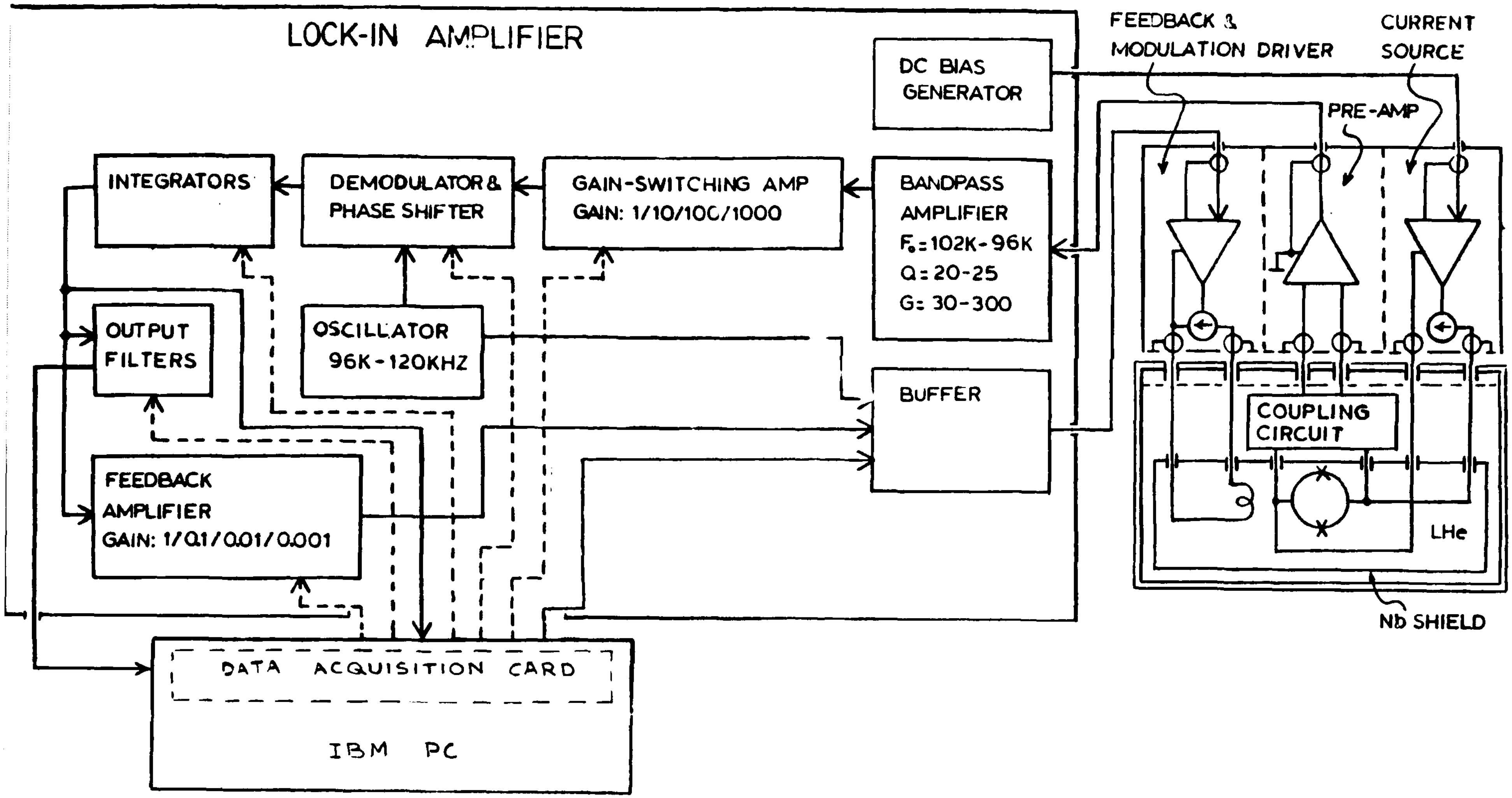


FIG-19 LOCK-IN AMPLIFIER AND FEEDBACK ALTERNATE CONTROL

APPENDIX I

Studies of Radiation Induced Change of Properties of Low T_c Josephson Junctions

We believe that a new technique of Low Temperature Scanning Electron Microscopy can be used to modify/on-line monitor changes in thin, high T_c films. Thus, the weak-junctions could be produced and used in superconducting circuitry. To test this concept we performed studies of low T_c superconductors, especially the Josephson Junctions.

Two series of experiments were performed[3] in collaboration with the group of Prof. R. Huebener, Tubingen University.

The electron beam irradiation of STJ's were performed using low temperature scanning electron microscopy (LTSEM).[1-3] Typical results are presented in Fig. 1, and show the tunneling conductivity in the normal state versus the number of beam electrons which have struck the tunneling window. This number was calculated from the irradiation time, the beam current, and the fractional portion of the total scanned area taken up by the tunneling window of 28.3 x 28.3 μm^2 area. Four different junctions were used in studies with electrons of different energy. Appreciable changes of the tunneling conductivity do not occur below the irradiation level of about 10^9 electrons striking the area of the tunneling window. With a window area of 812 μm^2 and beam energy of 26 keV, this threshold level corresponds to an energy deposited of about 3×10^{10} eV/μm^2.

In first studies using the LTSEM, the electron energy (E_e = 25 keV) was chosen so that they cross the oxide barrier and are absorbed in the bottom electrode. To test the influence of irradiation on superconducting properties, the collaboration performed a second series of tests with lower electron energy such that the electrons are stopped in the top layer of STJ and the effects of the oxide barrier can be neglected. We performed a series of experiments with variable energy of the beam, namely 2, 5, 10 and 25 keV. For lowest energies (2 and 5 keV), the electrons are stopped in the top layer of the junction. The irradiation dose at which we observe large change in the STJ's properties was monitored. It was 6.2 x 10^{11} electrons/μm^2, 1.4 x 10^{10} electrons/μm^2, 1.4 x 9 electrons/μm^2 and 7 x 10^7 electrons/μm^2, for E = 1,5, 10 and 25 keV, respectively. This data shows clearly that when the oxide barrier is not destroyed, STJ's operate properly after irradiation of about 10,000 MRad (see Fig. 1).

In the studies described above, we proved that the dominating effect is due to possible changes of the tunneling barrier under particle irradiation, since it is a highly delicate object with a thickness of only a few atomic layers. Further, the tunneling rate depends exponentially upon the height and width of the barrier potential. This argues against the use of STJ as radiation-hard devices, but the experimental results show that device withstood well radiation of up to 50 MRad at E_e = 25 keV and a few Gigarad at E_e = 2 keV. Thus for soft photons, e.g. X-rays laser, an exceptional radiation hardness was observed. However, due to the fragility of oxide, it is much more radiation soft for higher energy particles/radiation.

The above mentioned results are quite promising, they show that a controllable amount of oxide modification can be introduced by a few minutes of irradiation.

Furthermore, we should like to point out that radiation hardness of diverse superconductors varies vastly; the high T_c superconductors were shown to have their properties modified at 100 MRad doses. Ergo, even production of sub-micron weak-links seems to be technically feasible.

Ad: Radiation Hardness

1. F. Ruller-Albenque, "Effects d'irradiation dans les superconducteurs," page 1-70, preprint Lab. des Solides Irradies, Oct. 1987.
2. A.K. Drukier et al., "Proc. of Workshop on Low Temperature Detectors," 1988, Annency-le-Vieux, France.
3. R. Gross, Thesis, University of Tubingen (1987)
   R. Gross, R.P. Hubner, and U. Klaβ "Electron-Beam Irradiation of Josephson Tunnel Junctions," Proc. Workshop on Superconducting Particle Detectors, Torino, Oct. 26-29, 1987, ed. A. Barone.

Figure Captions:

Fig. 1: Dependence of the normal state conductivity G_{NN} of the superconducting tunnel junction (Pb-Au alloy) on irradiation dose for diverse electron energies (E_e = 2-25 keV).

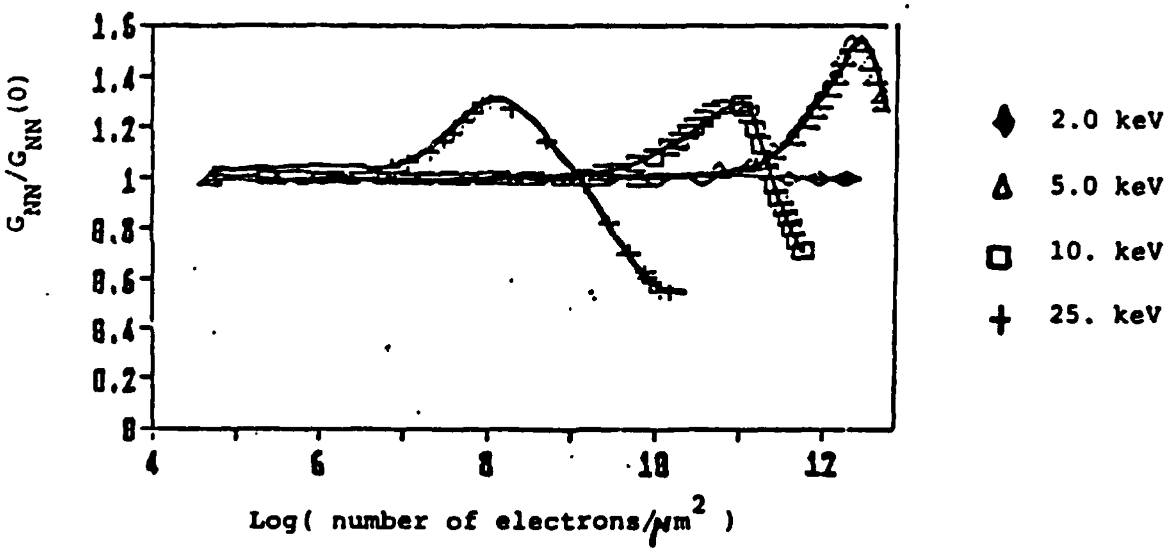


Fig.1

APPENDIX II

Low Noise Bipolar Preamplifier for DC-SQUID

ARC has developed a very low noise ($0.55nV/\sqrt{Hz}$) bipolar preamplifier which, due to its low input impedance, can be easily coupled to SQUID's. A modified preamp with optimal coupling to the LN_2 SQUID's produced by the ARC/NBS-Boulder, collaboration will be developed.

The PMI MAS-02 dual matched transistor pair has an intrinsic voltage and current noise near the theoretical limitations for bipolars, especially at low currents.

We verified that at T=25°C, I_C=1mA and h_{FE}=600, the MAT-2 is characterized by E_N=0.85 $nV/\sqrt{Hz}$ and I_N=1$pA/\sqrt{Hz}$ in accordance with PMI data sheets. At high currents, however, the effect of base spreading resistance ($R_{BB'}$) is to make E_N^2 increase as seen in the voltage noise vs. collector current curve.

Therefore,

$$E_N^2 = \frac{2(KT)^2}{qI_C} + 4KTb\sqrt{I_C} + \frac{2bqI_C 3/2}{h_{FE}} \qquad (1)$$

This provides a fairly accurate model for E_N^2, as was verified at I_C = 5mA, T ≈ 25°C, H_{FE} = 600, where E_N = 0.82 $nV/\sqrt{Hz}$. The min(E_N) = 0.76 $nV/\sqrt{Hz}$ at I_C = 2.5mA is obtained by minimalizing (1) with respect to I_C.

From the above, the total noise from the transistor pair with source resistance R_S can be modeled as

$$E_t^2 = 2(E_N^2 + I_N^2R_S^2 + 4KTR_S) \qquad (2a)$$

$$E_t^2 = 2(2(KT)^2/qI_C + 4KT(b\sqrt{I_C} + R_S) + 2qI_C((b\sqrt{I_C})^2 + R_S^2)h_{FE} \qquad (2b)$$

Thus, to reduce E_t^2 we should:

1) operate at I_C = 2.5mA;
2) reduce $R_{bb'}$ by paralleling; and
3) reduce R_S.

For N = number of parallel pairs we have

$$R_{BB'}(N) = R_{BB'}(1)/N = b\sqrt{I_C}/N \qquad (3)$$

and

$$E_T^2 = 2[2(KT)^2/qNI_C + 4KT((b\sqrt{I_C}/N)+R_S) + \frac{2qNI_C}{h_{FE}}[(b\sqrt{I_C})^2 + R_S^2] \qquad (4)$$

$$2qNI_C/h_{FE}\ [(b\sqrt{I_C}/N)^2 + R_S^2]$$

Table 1 is a comparison between theoretical values from (4) and the experimental values for different source resistances I_C and number of pairs in parallel. Particular attention was paid to E_N^2, since R_S is expected to be low. We conclude that it is more efficient for noise and power dissipation to parallel, rather than increase I_C to 2.5 mA. Therefore, we decided to use 3 transistor pairs at I_C (nominal) = 1.2 mA, achieving a theoretical noise performance of E_N = 0.48 = 0.45 nV/√Hz and I_N = 1.3=1.6 pA/√Hz, at room temperature. The calculated power dissipation is 160 mW.

Some other characteristics of this amplifier are summarized in Table 2; also part of the PMI - Application note 02 is provided for comparison and/or reference.

Equation (4) suggests a strong dependence of noise upon temperature. The OP27 and MAT-02 are specified for operation to T = -55°C, where the theoretical noise would be E_N = 0.37nV/√Hz for E_T = 0.61nV/√Hz for NF = 5 dB with R_S = 10Ω. We hypothesized that since the preamplifier has fairly wide bandwidth at room temperature (640 kHz), a lower noise level can be achieved if the bandwidth does not decrease below 160 KHz at temperatures near -55°C (our present application only calls for 100 KHz full gain). One experiment was to briefly immerse the preamplifier in liquid nitrogen (T ≈ 77°K) allow it to warm through the range of temperatures from 77°K to 300°K while measuring bandwidth and noise. It was found, as expected, that the transistor did "freeze out" at liquid nitrogen; but there was a point during the warm-up where E_T = 0.57 nV/√Hz, or E_N = .34nV/√Hz. We plan for further studies at $-193°C \leq T \leq -78°C$.

We concluded that, after improvement by a factor of 4-5, the bipolar preamplifier is an attractive candidate for a DC-SQUID preamp can compete with most FET preamplifiers.

Table 2 is a breakdown of the cost of each such preamp, in quantities of 10's. Thus, the preamp is not a major contribution to the price of DC-SQUID readout electronics.

Table 1: MAT-02 Transistor Noise; Theoretical vs. Measured Data for T = 25°C.

RS (Ω)	N	I_C (MA)	E_N theoret. (nV/√Hz)	E_T(nV/√Hz) Theoret.	Meas.	IN(pA/√Hz) Theort.	Meas.	Comments
50	1	2.0	.76	1.50	1.48			
200	1	2.0	.76	2.70	2.67			
50	2	1.0	.59	1.41	1.48	1.00	1.28	
50	2	2.0	.54	1.40	1.42	1.46	1.34	
50	3	1.5	.45	1.36	1.39			
10	3	1.5	.45	0.73	0.78	1.55		
50	3	2.0	.44	1.56	1.36			
N/A	3	1.0	.48	--	--	1.26		see Table 2

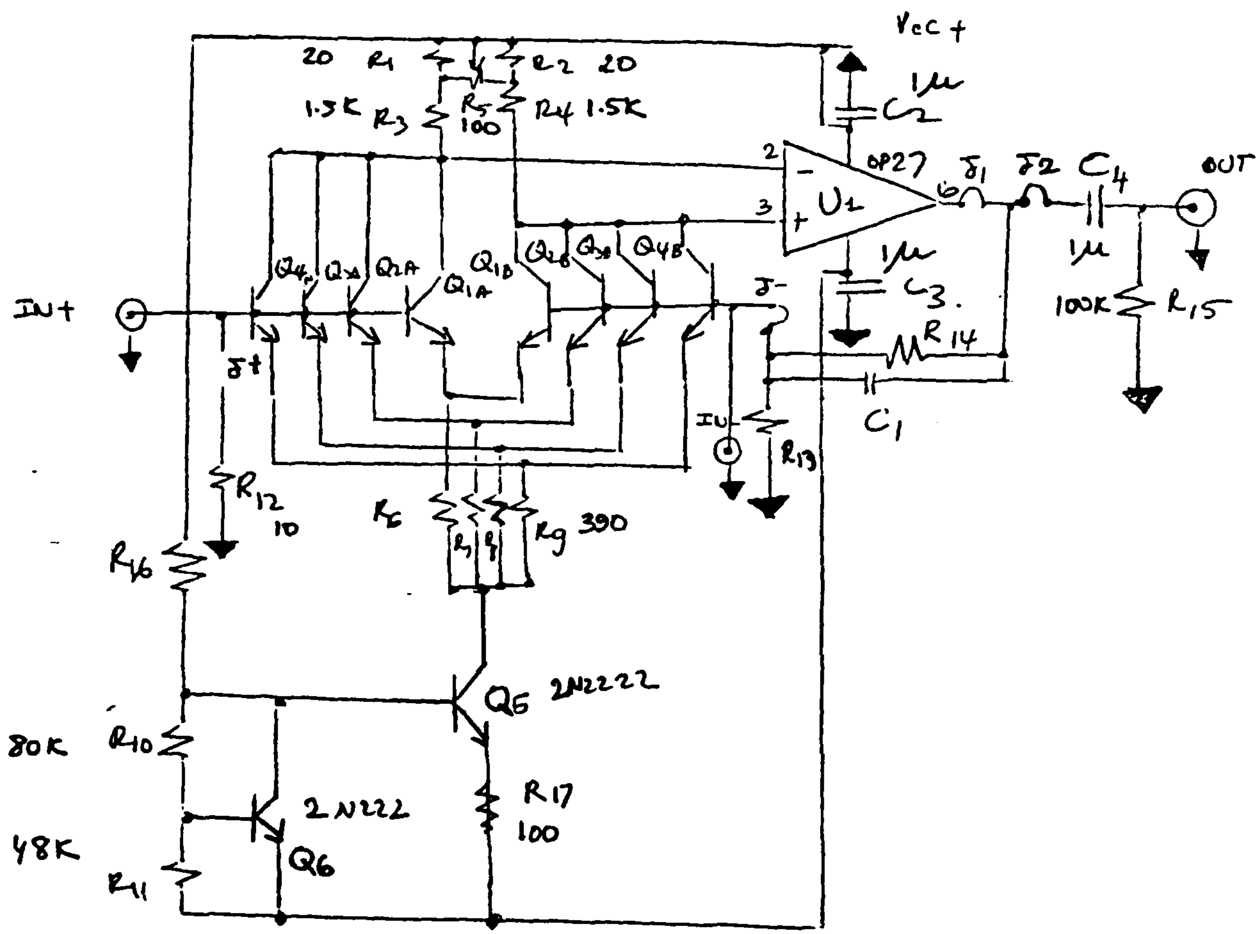
Table 2: Performance Characteristics of Bipolar Low Noise Preamp (T=25°C).

Parameter	PMIAN-102	Measured	Comments
Voltage-Noise $_{RMS}$ (F=100-100KHz)	E_N=0.5√Hz (F=1KHz)	E_t=0.78nV/√Hz E_t=1.36nV/√Hz	RS=10Ω(NF=5.6dB) R_S=50.0Ω(NF=3.7dB)
JN_{RMS} (F=100-100KHz)	1.5pA/√Hz --	-- --	See Table 1
Bandwidth (G=1000)	150KHz	640KHz	Measured at -3dB point
Slew Rate	2V/µS	1.8V/µs	
Open loop gain	3×10^7	--	
Common Mode Rejection Ratio	130dB --	-- --	
Input Bias	3µA	6.6µA	Need to balance input resistor with R_S to reduce offset.
Supply Current	10mA	9.83mA	

Table 3: Cost estimates

a) Bipolar Preamplifier

Component	Qty/Amp	Cost
Resistors (Metal Film)	10	≤ 5.00
Capacitors (NPO)	4	≤ 5.00
OP 27 AJ	4	20.00
MAT02AH	3	30.00
Box & Connectors	2	80.00
PC Board	1	25.00
Mounting	--	40.00
TOTAL		$ 205.00



Note: - Serials 1, 2, 3

- all resistors metal film - Values are approximate (1%)

APPLIED RESEARCH CORP. 8201 CORPORATE DR., LANDOVER, MD 20785		
APPROVED BY A DRUKIER	DRAWN BY N CAO	DATE 01/ 07/ 88
SOBPAMP SCHEMATIC REV 1		
DRAWING NO. S0004		SHEET NO.

APPENDIX III

Flux Counter

The flux counter and digital voltmeter (see Fig. 2) are required to obtain the magnitude of the SQUID output voltage. The flux counter is used, because the SQUID output voltage may be larger than the 10 volt range of the SQUID meter. Therefore, the flux counter is used to track the number of output overflows (each indicated by an output pulse from the SQUID auto-reset circuitry), while the voltmeter displays the modulo-10 of the voltage.

The flux counter consists of a series combination of two RAE 6600 Universal Counter/Timers. The circuit diagrams for these, along with the required modifications and interfacing to the SQUID, are shown in the following: Note the following points:

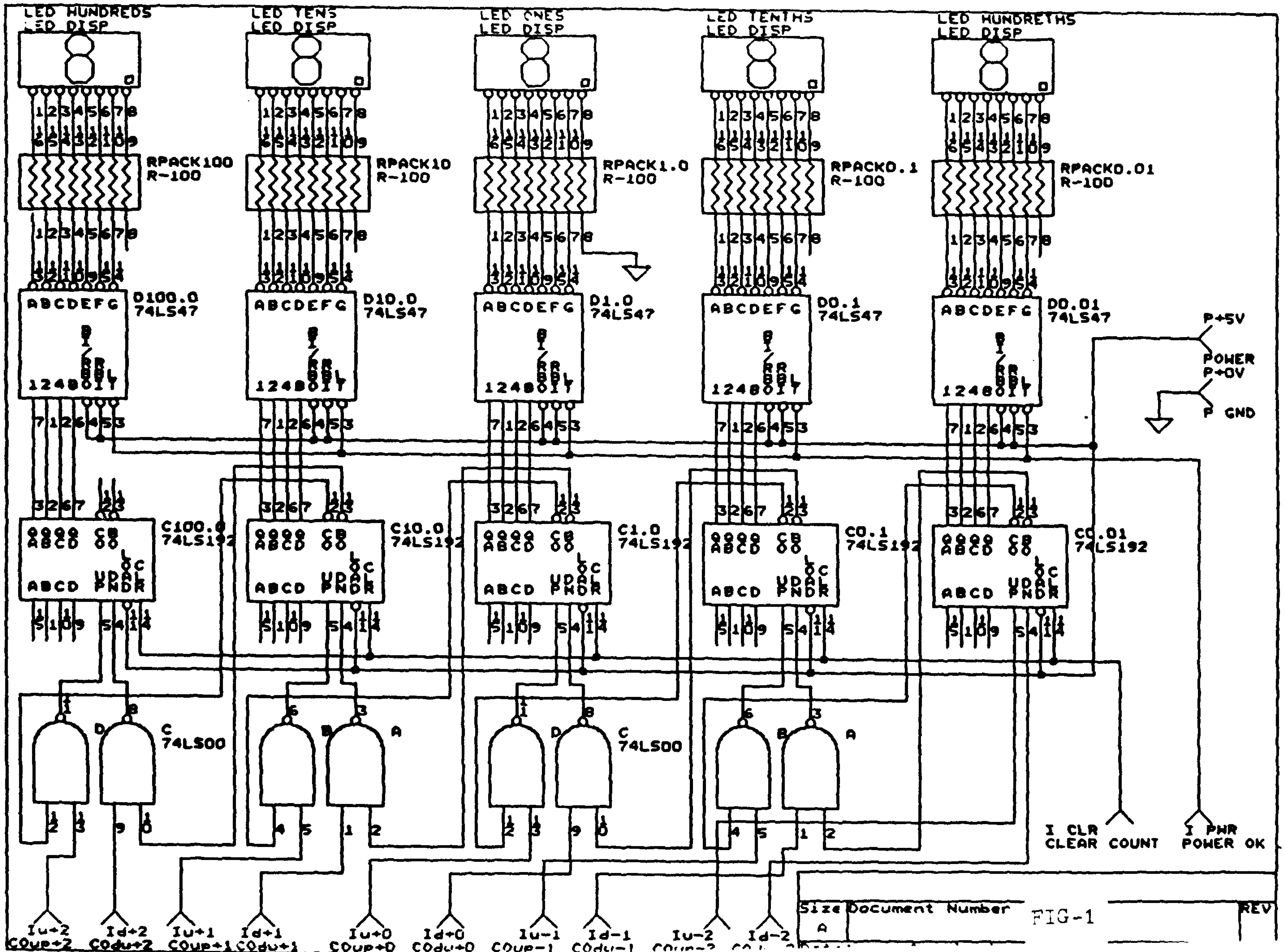
(a) each pair of series NAND gates on the count and sign inputs (see 3b) acts as an input buffer to the counter, to protect it from accidentally large inputs.

(b) the count and reset inputs to the counter (see 3a, top) are connected directly to the 7217 chip, rather than via the protective optoisolators provided by the manufacturers. These were avoided due misbehavior, but protection is maintained by the NAND gates (3b).

(c) the reset button (3b) is not chatterless, so on a one-shot debounce circuit was inserted to ensure that only a single pulse will reset the counter.

(d) the resistor connected between the reset inputs and V line (3b) ensures that the rest inputs remain at the V voltage until they are activated, in order to avoid unintentional inputs from stray static charges.

This flux counter has been built and is quite useful at the Univrsity of British Columbia. On the basis of our experience with the previously described flux counter, a new multi-input version of the flux counter has been designed (Fig. 1). The main features of the new flux counter is that it allows counting not only the integers portion of ϕ_o; but also up to the second decimal place. The above feature is crucial if the flux counter is used with savid electronic readout set to high gains ($100V/\phi_o$, $1000V/\phi_o$...) In such a condition, full analog scale (±10V) corresponds to a fraction of ϕ_o (1/10 or 1/100) and the autoreset system resets the readout everytime the output exceeds this. So in order to keep track of flux changes, it is necessary to change the decimal place on which the counter is advanced according to gain settings. The new version of the counter can be advanced on 1/100, 1/10, 1 and $10\phi_o$, corresponding to $1000V/\phi_o$, $100V/\phi_o$, $10V/\phi_o$, a $1V/\phi_o$, respectively.



LED HUNDREDS
LED DISP
LED TENS
LED DISP
LED ONES
LED DISP
LED TENTHS
LED DISP
LED HUNDRETHS
LED DISP
RPACK100
R-100
RPACK10
R-100
RPACK1.0
R-100
RPACK0.1
R-100
RPACK0.01
R-100
D100.0
74LS47
D10.0
74LS47
D1.0
74LS47
D0.1
74LS47
D0.01
74LS47
C100.0
74LS192
C10.0
74LS192
C1.0
74LS192
C0.1
74LS192
C0.01
74LS192
C
74LS00
C
74LS00
P+5V
POWER
P+0V
P GND
I CLR
CLEAR COUNT
I PWR
POWER OK
Iu+2
COup+2
Id+2
COdu+2
Iu+1
COup+1
Id+1
COdu+1
Iu+0
COup+0
Id+0
COdu+0
Iu-1
COup-1
Id-1
COdu-1
Iu-2
Id-2
Size
A
Document Number
REV

FIG-1

APPENDIX IV

Results of DC-SQUID Electronic Readout Tests

The ARC prototype of DC-SQUID electronic readout consists of a low noise preamplifier, lock-in amplifier, and feedback loop control system. The preamplifier was implemented as a separate unit and was designed to be mounted directly onto a LHe/LN_2 dewar to minimize the length of cables connecting the preamplifier and SQUID sensor. The lock-in amplifier and feedback loop control system was implemented in a single box together with all the switches and multiturn potentiometers (see Photo 1).

Two thin-film DC-SQUIDs were received from the National Institute of Standards and Technology (NIST) for testing the prototype SQUID electronics developed at ARC. The first SQUID tested had no signal coil and Nb-NbO-Pb Josephson tunnel junctions while the second SQUID had Nb-AlO-Nb junctions and a 1 μH signal coil inductance. The recently developed Nb-AlO-Nb tunnel junction technology allows more control over the junction fabrication procedure and is expected to result in SQUIDs with a lower 1/f noise corner frequency.

Other parameters of the SQUIDs are a SQUID loop inductance L = 100 pH, a critical current I_C = 20 μA, and an output impedance of R = Ω.

The SQUIDs were also tested with a copy of the Berkeley DC-SQUID electronics borrowed from Professor J.-P. Richard at the University of Maryland.

The output impedance of the SQUID was matched to the 6 kΩ noise impedance of the preamplifier with a tank circuit. The parameters of the tank circuit were an inductance L_T = 0.35 mH and C_T = 7.25 nF. The optimum noise temperature of the preamplifier was approximately 5 K.

For each of the above circuits, the noise frequency spectrum of the first SQUID has been measured. A test circuit is shown in Figure 4. The measurements were performed for two settings of integration time of lock-in amplifiers. One (fast setting) was chosen to maximize the system bandwidth when the second one (slow setting) was chosen to minimize the noise at low frequencies. The first of the above testing conditions corresponds to SQUID applications in which the maximal system stability is requested in the presence of external noise. The second one corresponds to the application in which maximal sensitivity over a long time is requested.

In Figures 1 and 2 respectively, the examples of noise frequency spectra for fast and slow integration settings with FET preamplifier are shown. In Figure 3, the spectrum measured with a bipolar preamplifier with slow setting is presented. Fig. 4 shows block diagram of the measurement circuit.

In Table 1, the test results are summarized. The values of frequency corresponding to 1/f corner (f_L), bandwidth (f_B), and noise level in the range f_L-f_B are presented.

The results of the test may be summarized as follows:

1. For the first SQUID, a white flux noise $\phi_n \approx$ 10-10 $\mu\phi_o/Hz^{1/2}$ was measured with both sets of electronics. With a SQUID inductance of L = 100 pH, this corresponds to an energy resolution S_E of $4x10^4$ h where we have used the standard definition $S_E = \phi^2{}_n/2L$ an h is Planck's constant divided by 2π. This energy resolution is approximately the same as the best commercial device.

2. There is no significant difference in the performance between the bipolar and FET preamplifiers. The FET preamplifier has lower white noise than the bipolar one. However, the bipolar preamplifier has a lower 1/f corner which means lower noise at very low frequencies than the FET one. In addition, the ARC bipolar preamplifier is about two times less expensive than the FET preamplifier.

3. The ARC electronic readout can be adapted to different SQUID sensors and to different impedance matching circuits (LC resonant circuit or superconducting transformer).

For the second SQUID, the flux noise $\phi_n \approx$ 40 $\mu\phi_o/Hz^{1/2}$ which corresponds to an energy resolution of 3 x 10^5 h. For this SQUID, a problem in the fabrication procedure resulted in noise junctions. Refinements in the procedure are expected to lead to low noise SQUIDs with S_E < 5 x 10^3 h and low 1/f noise. This energy resolution is a factor of 40 better than the commercial DC-SQUID sensors.

TABLE 1

Results of Tests of DC-SQUID Electronic Readouts
for NBS Nb-Nbo-Pb SQUID

	f_L[Hz]	f_B[Hz]	noise[$\mu\phi_n/\sqrt{Hz}$]
ARC prototype with FET preamp.	<1	2000	17
ARC prototype with Bipolar preamp.	3	500	25
UCB lock-in with FET preamp.	<1	2000	15

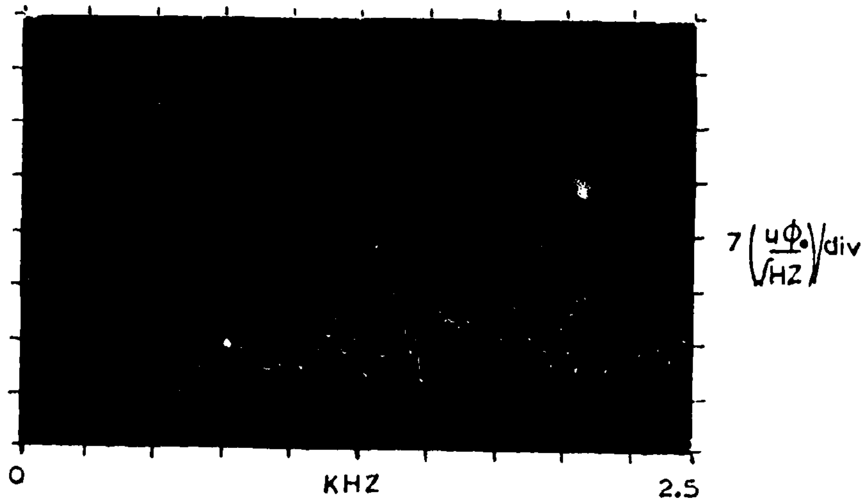


Fig. 1a. NIST SQUID with FET Preamp and UC Berkeley lockin (fast setting).

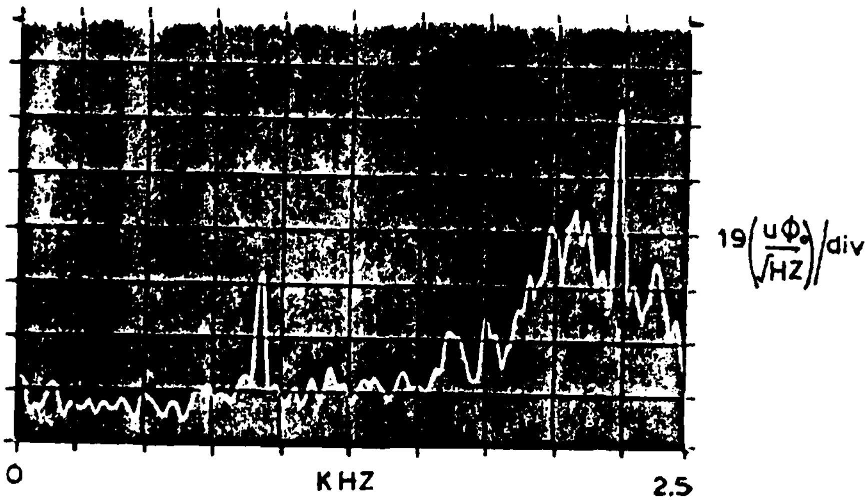


Fig 1b. NIST SQUID with FET Preamp and ARC Prototype II lockin (fast setting).

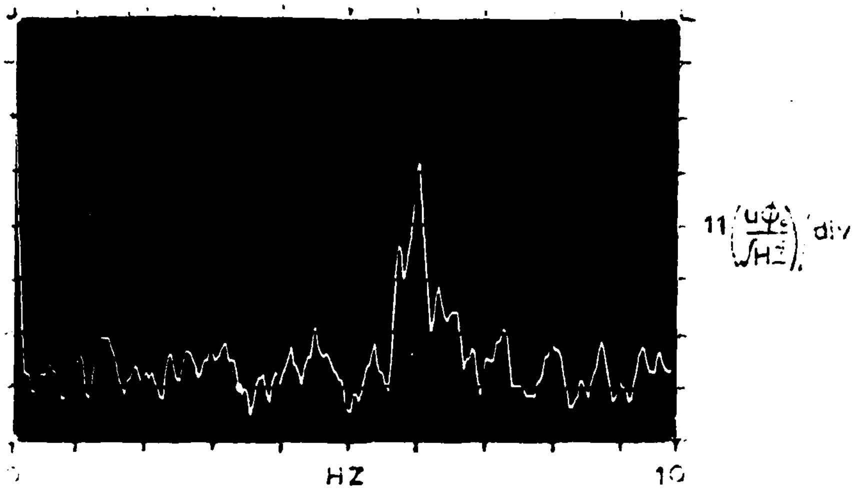


Fig. 2c. NIST SQUID with FET Preamp and
UC Berkeley lockin (slow setting).

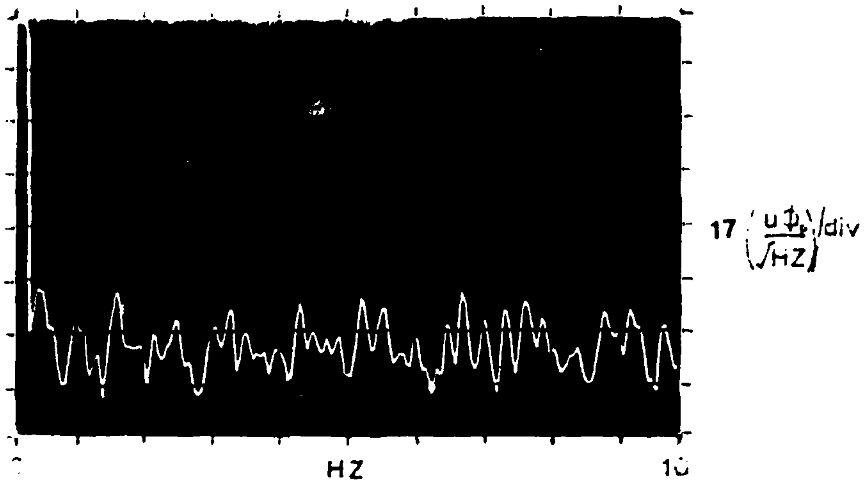


Fig. 2b. NIST SQUID with FET Preamp and
ARC Prototype II lockin (slow setting).

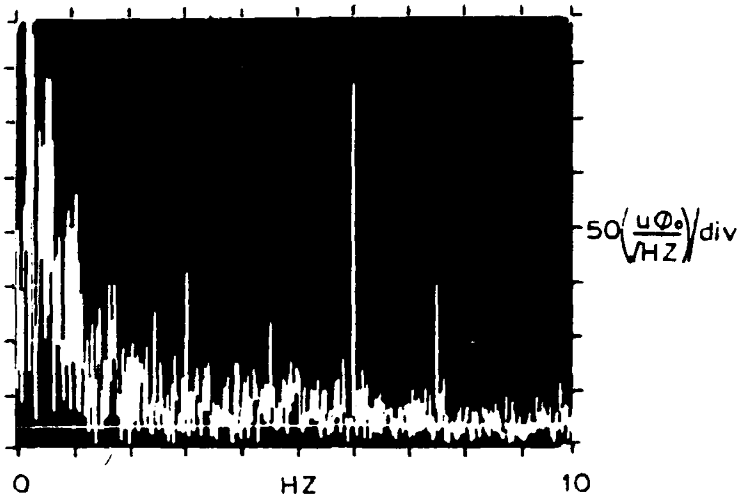


Fig. 3. NIST SQUID with Bipolar Preamp and

ARC PrototypeIlockin (slow setting).

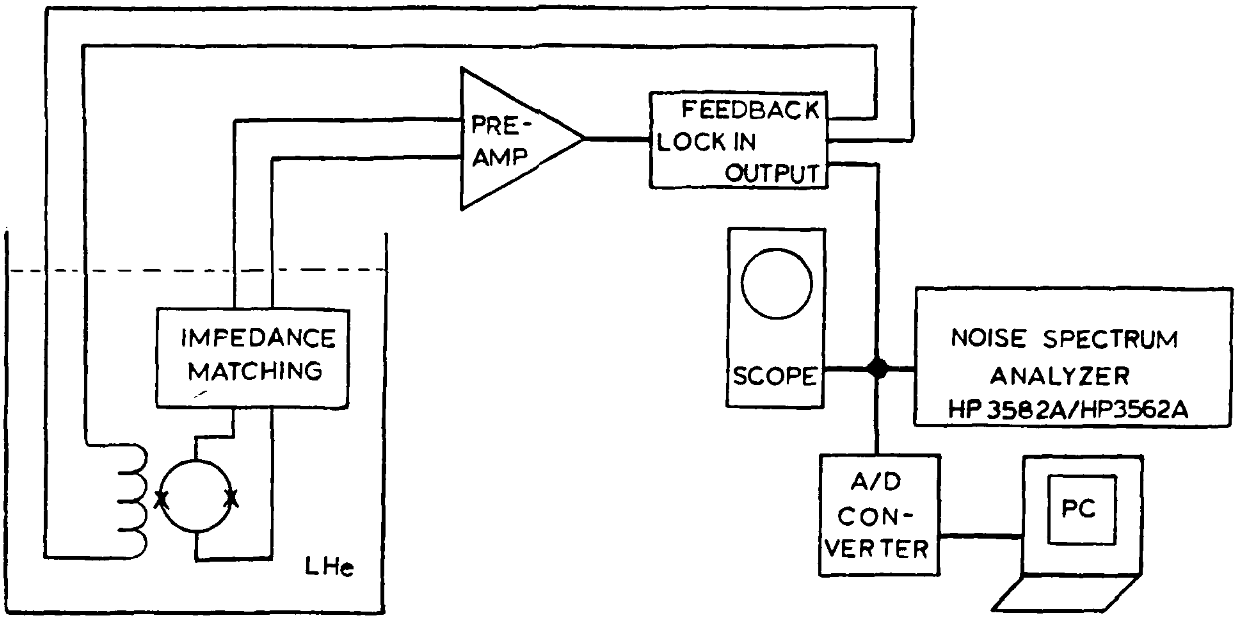


Fig.1. Test circuit used in noise measurements.

APPENDIX V

TEST OF BTi DC SQUID

While the commercial DC-SQUID sensors do not have the sensitivity that the thin-film devices have, they may provide a more reliable source of SQUID sensors. Even though they are less sensitive, they would still represent a significant factor of 10 improvement in energy resolution over the RF SQUIDs presently being used. Since several SQUID sensors and feedback electronics are needed, we have looked into the possibility of using a BTi sensor with the electronics being developed at ARC.

In Fig. 1, a schematic of the BTI DC-SQUID sensor is shown. The critical current of the junctions is a few microamps, the SQUID loop inductance is 200 pH, the signal coil inductance is $L = 2$ μH, and the feedback coil inductance is 0.2 μH. The 1.8 Ω resistor is used for balance in their SQUID biasing scheme.

To match the impedence of the SQUID to a low noise Field Effect Transistor (FET) amplifier, two transformers are needed. The transformer at the output shown in Figure 1 is at 4 K. The other transformer is placed at room temperature to limit the effects of line capacitance. To match between ~ 5 Ω of the SQUID to the 6 kΩ noise impedence of the FET preamp the electronics, the room temperature transformer was wound with a primary of 1.5 mH and a secondary of 32 mH to give a 4.5-1 turns ratio. Ferrox Cube 3B9 ferrite was used to achieve the necessary inductances in a reasonable volume and with negligible resistive losses. This sensor was tested with the ARC and Berkeley electronics. In this case, the ARC electronics contributed a significant amount of noise at the SQUID output. This excess noise is thought to result from grounding problems present in the prototype design. The improved electronics currently being fabricated by ARC is expected to eliminate this problem.

With the BTi sensor and the Berkeley electronics, the closed loop gain of the system was 35 mV/Φ_0. The noise spectrum is shown in Figure 2 from which a white flux noise of 65 $\mu\Phi_0/\mathrm{Hz}^{1/2}$ and a corner frequency of 10 Hz was determined. As a means of comparison, the noise spectrum obtained with the BTi sensor and electronics is shown in Figure 3. The white flux noise is 40-50 $\mu\Phi_0/\mathrm{Hz}^{1/2}$ ($S_E \approx 2 \times 10^4$ h) where the closed loop gain is 5.0 mV/Φ_0. The white noise achieved with the Berkeley electronics is 50% higher and results from grounding problems in the design. The grounding problems for the ARC electronics were even more severe. For the tests of the thin-film SQUIDs discussed in the previous section, the grounding was not as critical.

The low frequency corner frequency of 0.6 Hz (see Figure 3) measured with the BTi electronics is an order of magnitude lower than that obtained with the Berkeley electronics. This difference is due to the proprietary Dyna Bias circuitry of BTi. We plan to develop the noise reduction circuitry required for the BTi SQUID in Phase II.

We conclude that the BTi DC-SQUID sensor can be used with a standard flux locked loop. The addition of the second transformer provides the proper impedence matching that results in a low noise system. For

frequencies below 2 Hz, however, this hybrid system has less sensitivity than a typical BTi RF-SQUID system which has $\phi_n = 100\ \mu\phi_o/Hz^{1/2}$ and a 1/f corner frequency of 0.01 Hz. Even with the Dyna Bias circuitry of BTi, the RF SQUID has better sensitivity below ~0.5 Hz. Thus, for the BTi DC SQUID to be better than RF-SQUID, count rates must be greater than approximately one per second.

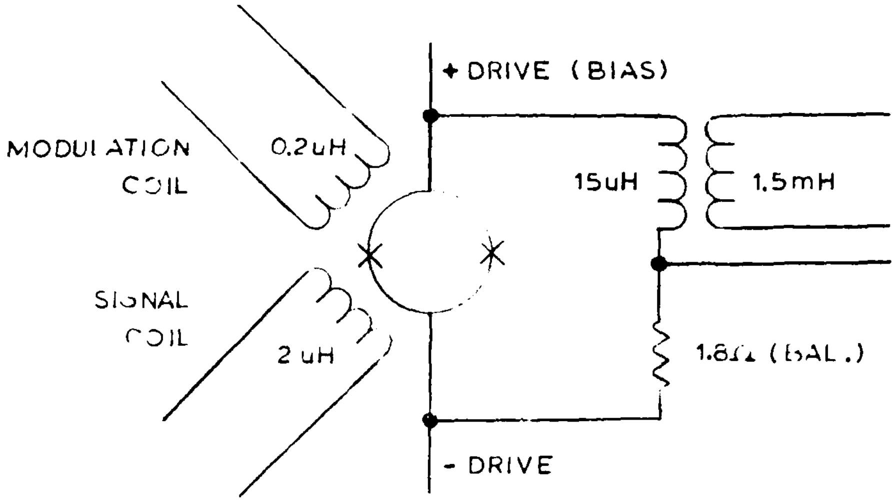


Fig. 1. Equivalent Circuit of the BTi SQUID sensor.

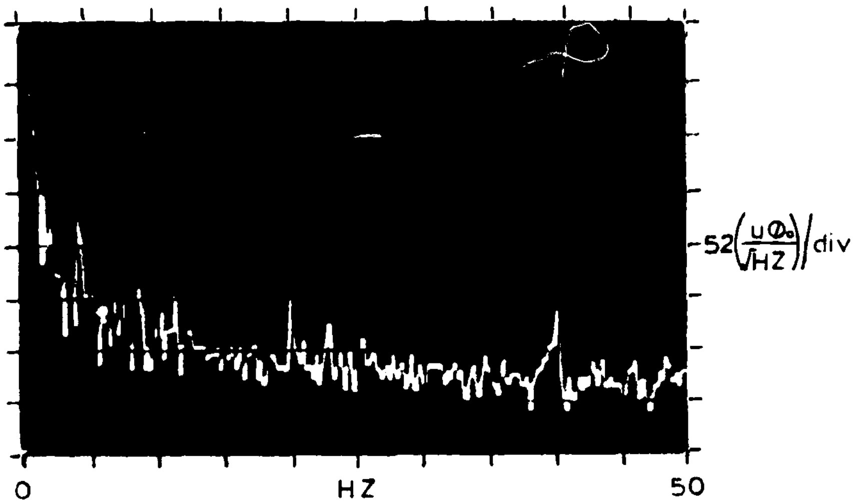


Fig. 2. Noise spectrum of the BTi SQUID sensor with Berkeley electronics.

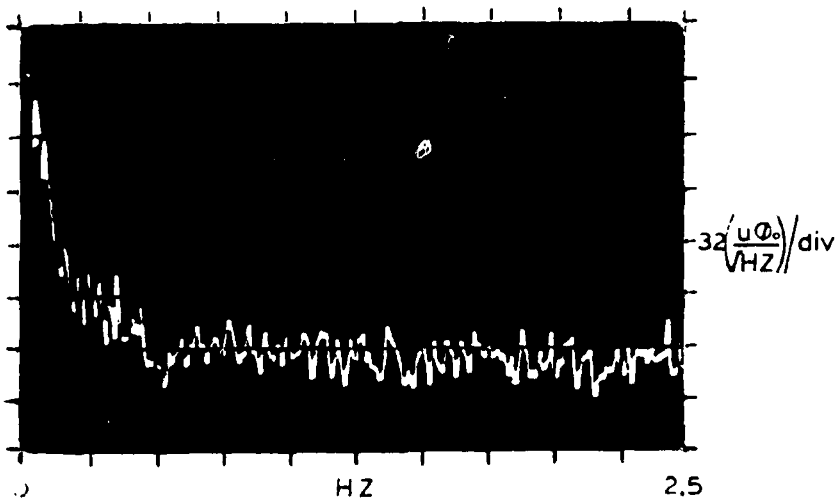


Fig. 3. Noise spectrum of the BTi SQUID system.